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ABSTRACT

Successful engine restart in space of an upper-stage vehicle using cryogenic propellants was accomplished for the first time with the flight of the Atlas-Centaur vehicle, AC-9. The problems unique to the restart of a vehicle using cryogenic propellants and the design concepts for solving these problems on Centaur are discussed. AC-9 flight data pertinent to the problems are also presented.

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SUMMARY

Atlas-Centaur AC-9, launched on October 26, 1966, was the first vehicle using cryogenic propellants that successfully demonstrated an engine restart in space. The successful restart verified the adequacy of the design concepts employed on Centaur for propellant management during the low-gravity orbital coast period, including the venting of propellant boiloff gases during coast. The ability to thermally precondition propellant supply and engine components for restart was also demonstrated. All engine flight data indicated that the restart was satisfactory.

The solutions to the problems of propellant management and thermal preconditioning on Centaur may differ from those of other vehicles, depending on the particular vehicle design. However, the general considerations required to solve these problems are applicable to all vehicles using croygenics and which require engine restarted after a coast period in space.

INTRODUCTION

Many high-altitude satellite, lunar, and deep-space missions use a two-burn transfer or parking orbit method of ascent in order to increase the time period available for launch. In the parking orbit method of ascent, the launch vehicle and payload are first inserted into a predetermined Earth orbit. After a variable-duration coast period, the engines on the vehicle are restarted and the payload is inserted into the desired trajectory.

Liquid oxygen and liquid hydrogen are more desirable than solid or storable liquid propellants because of the higher energy yield and the resulting increased payload capability. However, cryogenic propellants present unique problems when a two-burn method of ascent is used. The propellant boiloff gases must be vented during the coast phase to maintain tank pressures within allowable structural limits. Tank venting in the low-gravity coast phase environment requires proper control and positioning of the propellants to prevent venting of liquids. The propellants must also be positioned over the tank outlets to the engines in order to support engine restart. The propellant control problem is further complicated by propellant disturbances at engine first cutoff, during coast, and during the engine second start sequence.

Another problem unique to the use of cryogenic propellants is the thermal preconditioning of propellant feed lines and engine components that is required prior to engine second start. Solar and Earth thermal radiation, as well as possible hot gas impingement from auxiliary propulsion or attitude control systems, results in heating of these components during the coast phase. Engine pump cavitation will occur during the engine start sequence unless the propellant supply lines and engine pumps are prechilled to acceptable temperatures.

The purpose of this report is to present a brief summary of the problems unique to the restart of an upper-stage vehicle using cryogenic propellants, and the methods chosen to solve these problems for the Centaur vehicle. These problems are grouped into two general areas for the purpose of discussion: propellant management and thermal preconditioning. The pertinent AC-9 flight data which verified the effectiveness of the design concepts are also presented. A discussion of other design approaches for solving these problems is presented in reference 1.

GENERAL VEHICLE DESCRIPTION

The Atlas-Centaur vehicle, as shown in figure 1, is a two-stage vehicle manufactured by General Dynamics/Convair. The first stage is an Atlas intercontinental ballistic missile with the nose section modified to a constant 10-foot (3.05-m) diameter in place of a tapered nose section. The first stage, which weighs approximately 262 500 pounds (119 200 kg) at lift-off, consists of a jettisonable booster section, a sustainer and propellant tank section, and an interstage adapter. The propulsion system, manufactured by Rocketdyne, consists of two booster engines, one sustainer engine, and two vernier engines. Total lift-off thrust of the five engines is approximately 389 000 pounds (1 730 000 N). All engines are capable of gimbaling for vehicle directional control.

The Centaur stage is the nation's first hydrogen-fueled space vehicle. The tank structure, like the Atlas, is a thin-walled 301 stainless-steel, monocoque, cylindrical

structure, and is pressure stabilized to maintain its shape. The cylindrical portion is capped on each end by a stainless-steel bulkhead. A double-walled ellipsoidal stainless-steel inner bulkhead separates the liquid-oxygen and liquid-hydrogen tanks. Vehicle thrust is provided by two Pratt & Whitney 15 000-pound (66 700-N) thrust engines. The engines are turbopump fed and regeneratively cooled, and they utilize liquid hydrogen and liquid oxygen as propellants. Proper net-positive-suction head (NPSH) for the engine turbopumps is provided by a boost pump mounted at the outlet of each propellant tank.

Attitude control and propellant management, are accomplished on the Centaur stage with hydrogen peroxide engines. Four engines of 50-pound (222-N) thrust each are used for propellant settling. Four engines of 3-pound (13.3 N) thrust each are used for propellant retention. Two clusters of engines are used for attitude control. Each cluster has two 3.5-pound (15.6-N) thrust engines, and one 6-pound (26.7-N) thrust engine. Both the 50-pound (222-N) and 3-pound (13.3-N) engines may also provide pitch and yaw attitude control during propellant settling and retention periods. The locations of these engines are shown in figure 2.

COAST PHASE PROPELLANT MANAGEMENT

Propellant Management Requirements

During a coast period, the propellants are essentially in a weightless state (zero gravity) unless external forces are acting on the vehicle. Weightlessness creates a unique problem in cryogenic-propellant management. The absorption of thermal energy causes the cryogens to evaporate, which results in an increase in the tank pressures. The boiloff gas must be vented periodically in order to maintain the tank pressure within allowable structural limits. If the propellants are not settled, tank venting may release liquid along with the boiloff gases. Venting of liquids rather than gas is undesirable for three reasons: (1) excessive quantities of propellants may be vented overboard, which decreases payload capability, (2) larger disturbing torques may be produced on the vehicle if the venting is not symmetrical, and (3) liquid venting may not decrease tank pressures as desired and may thus result in overpressurization of the tank. Also, a scheduled engine restart is not certain unless liquid is maintained at the tank outlets to the engines during the restart sequence.

The problem of propellant management was recognized early in the Centaur development program. However, very little was known about propellant behavior in a full-scale vehicle during a low-gravity coast. Until the flight of the fourth Atlas-Centaur (AC-4), the importance of kinetic energy inputs to the propellants was not fully recognized. In the low-gravity environment of coast, even a relatively small amount of propellant kinetic

energy may result in large amplitude slosh waves or liquid splashing within the tanks. The coast and engine restart phase of the AC-4 flight was not successfully accomplished because liquid hydrogen was vented during the coast. The vented liquid expanded in the vacuum of space with the plume impinging on the vehicle. The pressure forces resulted in unbalanced torques on the vehicle greater than the attitude-control-system capability, and vehicle tumbling occurred. Analysis of the flight data revealed that the liquid-hydrogen venting was a direct result of energy input into the propellant during powered flight and during the initial phase of the coast period prior to the first venting of the hydrogen tank.

A complete reevaluation of Centaur propellant management requirements was made and design changes were incorporated into the AC-8 vehicle. The analysis and design concept proved to be adequate by the successful management of propellants during the AC-8 flight. Details of the analysis, design changes, and AC-8 flight results are discussed in references 2 to 6.

Because of a vehicle problem unrelated to propellant management, the engines were not successfully restarted on the AC-8 flight. Successful restart of the Centaur engines was demonstrated for the first time on the AC-9 (ref. 7).

Successful management of the propellants during the coast phase depends on:

(1) Identifying the source and determining the magnitude of the energy imparted to the propellant at engine first shutdown, during the coast, and during the engine restart

(2) Providing a means for dissipating this energy rapidly

(3) Retention of liquid in a location to allow venting of boiloff gas only

(4) Retention of liquid to enable liquid flow to the engines for restart

The energy imparted to the propellants during engine first shutdown, coast, and engine restart can be generated by or consist of the following:

(1) Backflow through propellant feed lines at engine shutdown

(2) Return flows from pump bleeds and recirculation lines

(3) Structural relaxation on thrust termination

(4) Attitude-control engine firings

(5) Propellant sloshing

(6) Propellant convective currents from thermal heating

(7) Unbalanced gas and/or liquid venting

(8) Pressurization gas flow impingement on the liquid surface

AC-9 Configuration

On the Centaur vehicle, return flows to the liquid-hydrogen tank resulted from a volute bleed line on the liquid-hydrogen boost pump and from recirculation lines connected to the engine liquid-hydrogen supply lines. These return flows were major contributors to the total-energy input to the liquid hydrogen at first main-engine cutoff on AC-4. In the AC-8 and AC-9 vehicles, energy dissipators were installed on the lines at the entrance into the tank (figs. 3(a) and (b)), for the purpose of reducing the energy level of these two return flows.

Changes in the coast-phase thrust level and sequence were incorporated following the AC-4 flight. The AC-4 vehicle had 4 pounds (18 N) of axial thrust continuously applied during the entire coast period. For the AC-8 and AC-9 flights, a continuous thrust was also applied on the vehicle, but the magnitude was increased and varied during the coast period, as shown in figure 4. For 76 seconds after main-engine first cutoff, 100 pounds (445 N) of thrust was applied to the vehicle to settle the propellants. After 76 seconds, the thrust level was reduced to 6 pounds (26.7 N) to retain the propellants in the rear of the tanks. Forty seconds prior to the main-engine second start, the thrust level was again increased to 100 pounds (445 N). The higher thrust levels were used to suppress any propellant disturbances associated with the engine shutdown and start sequences.

A slosh baffle was also added to the liquid-hydrogen tank as shown in figure 5. The thrust schedule and slosh baffle combination was designed to dissipate the residual energy from the return line flows, plus all other energy inputs to the liquid-hydrogen mass at main-engine first cutoff and during the coast period. Energy dissipation was accomplished by the slosh baffle damping the liquid motion.

The criteria used in the baffle design and selection of the thrust schedule during the coast period were that (1) the liquid spray and wave height resulting from liquid-hydrogen disturbances would never reach the hydrogen tank vent exit and (2) the propellants would be retained over the tank outlets to the engines for engine second start.

Subsequent to the AC-4 flight, an energy dissipator was also installed on the hydrogen-tank pressurization line at the point of entry into the tank, as shown in figure 6. This design change was made to reduce the pressurant-gas velocity from approximately 2000 to 20 feet per second (610 to 6 m/sec). A high-velocity pressurant-gas jet impinging on the liquid-hydrogen surface during the main-engine second start sequence, combined with the low-gravity environment, could result in disturbance (splashing) of the liquid-gas interface and cooling of the ullage gas. This, in turn, could result in a reduction of tank pressure below the level required for satisfactory boost-pump operation.

In conjunction with the installation of the energy dissipators and slosh baffle in the hydrogen tank, a balanced-thrust hydrogen-vent system was installed on AC-9. The vent system was identical to the one successfully flown on AC-8 (see fig. 7). The system was

designed to provide nonpropulsive, nonimpinging gas venting during the coast phase.

The liquid-hydrogen boiloff gases were vented out of the top of the tank through the vent valves and into the torus assembly. The flow was then discharged radially in opposite directions. Convergent nozzles 1.35 inches (3.43 cm) in diameter were installed at the vent duct exits to provide flow limiting control and to serve as metering devices. The inlet lines to the vent valves were inclined slightly to allow drainage of any entrained liquid back into the tank. A deflector plate was inserted below the duct inlet to prevent liquid from sloshing directly into the vent line.

The torus compensated for any unequal flow splitting at the vent-valve discharge and provided pressure equalization at the exit nozzles for thrust cancellation. The sizing of exit nozzles was dictated by internal duct velocity, vent flow rate, and tank-pressure requirements.

Instrumentation

The AC-9 hydrogen tank was instrumented with 31 liquid-vapor sensors and 16 ullage temperature sensors (fig. 8). These sensors were installed to provide data on liquid-hydrogen motion in the tank and the hydrogen ullage temperature profile during flight. In addition, the temperature sensors served as liquid-vapor sensors. (For further details, see ref. 8.)

Also installed on the hydrogen tank were 50 temperature patches to monitor the tank skin temperature. The liquid-oxygen tank was also instrumented with four skin-temperature patches. The locations of these temperature patches are shown in figure 9.

AC-9 Flight Results

Liquid-hydrogen behavior. - Immediately following main-engine first cutoff, momentary wetting of sensors located 14 inches (0.36 m) (station 316.4) above the liquid surface at engine cutoff was noted indicating some minor propellant disturbances (see fig. 10). However, these sensors were dry by 10 seconds after engine cutoff and remained dry throughout the remainder of the coast period.

During the engine second start sequence (T+1995 sec to T+2035 sec) the liquid/vapor sensors showed that the liquid hydrogen remained completely settled and available for engine start (see fig. 10). Engine start occurred as planned, and no unusual propellant motion was observed during engine second firing. The sensors responded to the decreasing liquid level during engine firing. It is concluded that the method of liquid-hydrogen control was completely satisfactory for the entire coast and restart phase.

Liquid-oxygen behavior. - Data from the four liquid-oxygen tank skin-temperature patches are presented in figure 11. Immediately following the main-engine first cutoff, two temperature patches indicated a sharp drop in temperature. This temperature drop was caused by liquid sloshing along the tank walls. The temperature patches were located approximately 6 inches (15 cm) above the liquid level at engine shutdown.

During the coast phase, the temperature patches indicated off-scale high, (greater than 210° R (117 K)). This was caused mainly by solar heating. The liquid level was below the patches, and no wetting was noted during the coast. This indicated that the liquid oxygen remained settled during the coast.

Hydrogen-tank ullage temperature survey. - Shortly after the main-engine first cutoff (T+650 sec), some temperature oscillations occurred in the hydrogen ullage at the forward end of the vehicle. These oscillations were probably the result of propellant spray and disturbances caused by transients at main-engine first cutoff. However, no wetting of the sensors by liquid hydrogen was noted.

The first venting of the hydrogen tank occurred 230 seconds after main-engine first cutoff. Two sensors (CF155T and CF158T, see fig. 8), located near the forward end of the vehicle, showed an immediate temperature decrease, as shown in figure 12. The rapid drop in temperature indicated that the warm gas in this area was being vented and replaced by cooler gas from the lower portion of the tank. Intermittent hydrogen venting continued throughout the remainder of the coast. Response of the sensors located in the forward end of the tank to the hydrogen venting is shown in figures 12(a) and (b). The temperature in the ullage region during the venting period was stratified with warm gas in the forward portion of the tank and cold gas nearer the liquid surface.

During the coast phase, 40 pounds (18.2 kg) of gaseous hydrogen were vented overboard. Venting of hydrogen gas through the balanced vent system produced negligible disturbances on the vehicle, indicating that the vent system operation was completely satisfactory.

At main-engine second start minus 40 seconds (T+1995 sec), the hydrogen tank was pressurized with gaseous helium in preparation for engine start. The introduction of warm helium into the tank caused the ullage temperature at several locations to increase sharply as the warm helium passed over the sensors. Three sensors located at the forward end of the tank (CF155T, CF158T, and CF160T) indicated a rapid temperature rise immediately after tank pressurization was initiated and then a more gradual, but pronounced, decrease as cooling of the helium gas in the ullage occurred. After main-engine second start, with approximately 1-g acceleration on the vehicle and tank pressurization terminated, free convective currents caused these three sensors to indicate a temperature rise again as the cooler and more dense ullage gas moved to the aft end of the tank. The sensor located at station 167 (CF155T) indicated the greatest temperature rise after engine start because of local heat input from the forward end of the vehicle.

During the hydrogen-tank pressurization, none of the liquid-vapor sensors above station 340 were wetted, which indicated that the energy dissipator was effective in reducing the pressurant-gas velocity to a level which prevented the liquid from splashing into the ullage (see fig. 10). Tank ullage pressure continued to increase during the entire pressurization period. Any major splashing or disturbance of the liquid-vapor interface would have resulted in a tank pressure decay during this period.

During the main-engine second firing period, the hydrogen-tank ullage temperatures remained stratified. All ullage temperature sensors indicated a gradual temperature increase as the liquid level decreased (see fig. 12(c)).

PROPELLANT SUPPLY SYSTEM DESCRIPTION AND OPERATION

Boost Pumps

The AC-9 Centaur vehicle used boost pumps to supply conditioned propellants to the main-engine turbopumps at the required net-positive-suction pressures. A centrifugal boost pump was mounted at the outlet of each propellant tank and submerged directly in the fluid (fig. 3(a)). Submerging the pump eliminated the need to prechill the boost pumps prior to operation. Each boost pump was powered by an individual gas-driven turbine. Cutaway views of the boost pumps and turbine drives are shown in figure 13. Superheated steam and oxygen from the catalytic decomposition products of 90 percent concentration hydrogen peroxide were supplied to drive the turbines. Constant turbine power was maintained on each unit by metering the hydrogen peroxide through fixed area orifices upstream of the catalyst bed. A flow schematic of the hydrogen peroxide supply system is shown in figure 14.

The boost pumps were designed to start and operate without cavitation at a very low value of net-positive-suction pressure. The net-positive-suction pressures required during the period between boost-pump start and main-engine start were provided by injecting a small quantity of helium gas into each propellant tank. After main-engine ignition, the engine thrust and liquid level provided sufficient acceleration head to supply the required boost pump inlet net-positive-suction pressures.

The boost pumps were also designed to operate without caviation, when propellant flow to the engines was zero, by continuously bleeding a small quantity of liquid from each pump discharge back into the respective propellant tanks.

Propellant Supply Lines

System description. - The propellant supply lines located between the boost pumps and the engine inlets are shown schematically in figure 15. Both the liquid-hydrogen and liquid-oxygen supply lines were made of thin-wall stainless-steel tubing. Approximately 0.75 inch (1.9 cm) of ribbed, low-density foam insulation was bonded directly to the supply lines. Thermal radiation protection was provided by thin reflective aluminized plastic film tape wrapped over the foam insulation. Small recirculation lines with flow-limiting venturis were connected to the supply lines immediately upstream of the main-engine inlet valves. The purposes of these recirculation lines were to remove trapped gases from the propellant supply lines prior to main-engine first start and to aid in supply-line chilldown prior to main-engine second start.

Propellant supply-line preconditioning. - Analytical studies conducted prior to the launch of AC-8 indicated a strong possibility that liquid-hydrogen and liquid-oxygen would not be retained in the propellant supply lines throughout a 25-minute orbital coast period. Space heating results in heat transfer through the protective insulation located on the supply lines and eventual evaporation of the liquids. Under normal 1-g conditions, the gases produced by the liquid evaporation would be displaced by the liquid and removed from the lines, either through the recirculation lines or by bubbling back through the main supply lines to the tanks. However, in the low-gravity environment of orbital coast, it was predicted that the gases would gradually displace the liquid as evaporation progressed. Calculations showed that Bond numbers (ratio of inertial to surface tension forces) in excess of 3.4 were required to ensure that liquid would displace the gas as it evolved. The Bond numbers calculated for the propellant supply lines during the 6-pound (26.7-N) thrust propellant retention phase of the coast were only 0.6 and 2.6 for the liquid-hydrogen and liquid-oxygen lines, respectively.

Temperature data obtained from transducers located in the propellant supply lines on AC-8 verified that the liquids did not remain in the propellant supply lines during the coast period (see fig. 16). Transducers in the liquid-hydrogen line indicated that it started drying approximately 3 minutes after the start of the coast period, and was completely dry 6 minutes after start of the coast period. The liquid-oxygen line started drying after 10 minutes of coast and was completely dry 21 minutes after start of the coast period.

The engine inlet temperature transducers on AC-8 indicated that the C-1 engine branch of the liquid-oxygen line dried approximately 2 minutes sooner than the C-2 engine branch. This more rapid drying was due to impingement heating of the C-1 branch line by the exhaust plumes of one of the 50-pound (222-N) thrust propellant settling engines and one of the 6-pound (26.7-N) thrust propellant retention engines which fired during the coast.

After the propellant supply lines were emptied of cryogenic liquids, the temperature of the metal in the lines increased rapidly from the space and exhaust plume impingement heating during the coast. The rate of temperature rise was dependent on the amount of radiant energy on the lines. The amount of incident radiant energy was, in turn, dependent on the vehicle orientation with respect to the Earth and Sun. Theoretical maximum propellant supply-line average metal temperatures were calculated prior to the AC-9 flight assuming that one side of each line was impinged by solar radiation and the other side by Earth thermal radiation for the entire 25-minute maximum coast period. In addition, it was assumed that the liquid-hydrogen line was empty of liquids at the start of the coast and that the liquid-oxygen line was empty after 10 minutes of coast. Impingement heating of the C-1 branch of the liquid-oxygen line was also assumed.

These predicted maximum supply-line temperatures were used in special ground testing of the engine and propellant supply systems prior to the AC-9 flight to establish the inflight chilldown requirements for a satisfactory engine restart. With the propellant supply lines relatively warm compared with the cryogenic liquid temperatures, precautions must be taken to ensure adequate cooldown of the lines prior to restart of the engines in space. Failure to cool the lines adequately would result in boiling of the cryogenic liquids as they entered the warm supply lines. The available net-positive pressure at the main-engine turbopump inlets would be reduced, and large quantities of gas bubbles would be introduced to the liquid flow to the engines during the critical start phase.

The Centaur propellant supply-line cooldown was accomplished by flowing a small quantity of liquid through the lines during two separate time periods prior to engine restart. The first period of flow began when the boost pumps accelerated to operating speed. A small flow of liquid was forced through the supply lines, the recirculation lines, and back into the propellant tanks. After the boost pumps attained operating speed, the main-engine inlet valves were opened, which permitted an increased flow of liquids through the propellant lines. This flow passed through the main-engine turbopumps and chilled the main-engine turbopumps as well as the supply lines.

The AC-9 chilldown sequence selected from the ground tests (using the maximum predicted temperatures) was to start the boost pumps 28 seconds prior to main-engine start, and to open the main-engine inlet valves 17 seconds prior to main-engine start. The ground tests indicated that the 11 seconds of recirculation flow and 17 seconds of overboard chilldown flow prestart was adequate for a satisfactory engine restart.

AC-9 Flight Results

The propellant supply-line drying history for the AC-9 coast period is shown in figure 16. The data presented were obtained from temperature transducers located in the propellant supply lines (fig. 15). The liquid-hydrogen supply line started drying

2.5 minutes after start of the coast and was completely dry 5.5 minutes after start of the coast. The liquid-oxygen branch line to the C-1 engine was at least partially dry after 7.5 minutes of coast as indicated by the C-1 engine inlet temperature transducer. However, the C-2 engine oxygen pump inlet transducer and the oxygen boost-pump discharge transducer indicated liquid temperature throughout the coast period. Apparently, the C-2 branch of the liquid-oxygen line was shaded from the Sun and Earth during most of coast which resulted in a low net heat flux into the line. Drying of the C-1 liquid-oxygen line can be partially attributed to plume impingement heating from the propellant settling and retention engines mentioned previously.

It should be noted that the liquid-hydrogen line and the C-1 branch of the liquid-oxygen line dried more rapidly on AC-9 than on AC-8 because of the higher solar heating on AC-9 compared with AC-8. AC-9 was a daytime launch with solar heating of the aft portion of the vehicle during the last 4 or 5 minutes of the coast. AC-8 was a night launch with no solar heating.

The engine turbopump inlet temperature data for the AC-9 main-engine second start sequence are shown in figures 17 and 18. Liquid-oxygen was present at the main-engine turbopump inlets prior to boost pump start. However, liquid-hydrogen was not present at the turbopump inlets until after start of the inflight chilldown. As shown in the figures, both the oxygen and the hydrogen turbopump inlet temperatures stabilized at the tank saturation temperature within 4 seconds after start of inflight chilldown, which indicated that propellant line cooldown was completed at this time. The rise in liquid-oxygen turbopump inlet temperature in the period between boost-pump start and start of flight chilldown was a result of heat input to the liquid by the boost pump. The C-2 engine liquid-oxygen pump inlet temperature started dropping prior to start of inflight chilldown as the warm gas and liquid in the duct was slowly expelled through the recirculation line back into the tank.

The calculated boost-pump-inlet net-positive-suction pressures during the AC-9 main-engine second start sequence are shown in figure 19. Ground tests have shown that the boost pumps can operate without cavitation at net-positive-suction pressures of 0.4 and 0.07 psi (0.27 and 0.05 N/cm^2) for the liquid-oxygen and the liquid-hydrogen pumps, respectively. The net-positive-suction-pressure values calculated for AC-9 were well above 0.07 psi (0.05 N/cm^2) for the liquid-hydrogen pump during the entire start sequence. The indicated net-positive-suction pressure for the liquid oxygen pump was less than 0.4 psi (0.27 N/cm^2) during the 2-second period immediately following boost-pump start. However, analysis of the pump performance indicated that the actual net-positive-suction pressure was adequate during this time because the characteristics of cavitation (a sharp increase in speed accompanied by a drop in pump headrise) were not evident.

All performance data for the boost pumps indicated that both units functioned prop-

erly during the main-engine second start sequence. Liquid-hydrogen boost-pump turbine speed and pump differential pressure-rise data for the start sequence are presented in figures 20 and 21. Similar data for the liquid-oxygen boost pump are presented in figures 22 and 23. For comparison, the expected performance bands based on ground-test experience are shown on each figure. All flight performance data were within the expected bands. Both turbines accelerated to a steady-state operating condition prior to main-engine second start in approximately 20 seconds. Both turbine speed and pressure rise across the pump dropped rapidly at main-engine second start because of the large increase in propellant flow to the engines. Oscillations in the pump pressure-rise curves at start of inflight chilldown and at main-engine second start are a result of pressure surges in the propellant supply lines caused by rapid opening of engine valves.

MAIN-ENGINE SYSTEM DESCRIPTION AND OPERATION

System Description

The two YRL10A-3-3 rocket engines used on AC-9 were a regeneratively cooled turbopump-fed engines using liquid hydrogen and liquid oxygen as propellants. Each engine had a rated thrust of 15 000 pounds (66 700 N) at an oxygen to hydrogen propellant mixture ratio of 5 to 1. The minimum specific impulse was 439 seconds with a nozzle expansion area ratio of 57 to 1. A schematic of the engine system is shown in figure 15 (see ref. 9).

During steady-state operation, the boost pumps supplied each engine with liquid oxygen and liquid hydrogen. The liquid oxygen passed through a single-stage engine pump and then through a mixture ratio control valve directly into the combustion chamber. The liquid hydrogen passed through a two-stage engine pump and then through the thrust-chamber jacket. This routing of hydrogen flow served the dual purpose of cooling the thrust-chamber walls and of increasing the hydrogen temperature and energy level. The hydrogen was then expanded through a turbine which drove both the hydrogen and oxygen. pumps. Finally, it was injected into the combustion chamber.

Operating Requirements

Main-engine specification requirements for engine start were that (1) the thrust-chamber average metal temperature must be between 250° and 570° R (139 to 316 K), (2) the engine pumps must be chilled prior to main-engine start to ensure satisfactory pumping characteristics, and (3) the engine pump inlet temperatures and pressures during the final portion of the prechill period and during main-engine operation must lie within the shaded regions of figures 24 and 25.

During steady-state operation, the energy necessary to drive the turbine was obtained by the transfer of heat from the products of combustion through the thrust-chamber walls to the hydrogen. For the engine start transient, however, the energy must be obtained from residual heat within the thrust-chamber walls. This requirement is reflected in the specified limits for the thrust-chamber average metal temperature.

A 17-second prechill prestart period was provided prior to the main-engine second start to cool the pumps and to ensure that liquid conditions existed at the engine inlets. This prechill was provided by opening both the oxygen and hydrogen inlet valves. The oxygen flowed through the pump and was expelled through the engine combustion chamber. Hydrogen was vented overboard through two separate cooldown valves on each turbopump: a cooldown valve was provided immediatedly downstream of each stage of the pump. The engine main fuel shutoff valve prevented hydrogen from being vented through the combustion chamber during the prechill period (see flow schematic, fig. 15).

Previous experience has shown steady-state operating temperatures for the hydrogen and oxygen-pump housings to be approximately 60° and 180° R (33.3 and 100 K), respectively. At the time of main-engine start command, hydrogen and oxygen pump-housing temperatures must be at, or decreasing rapidly toward, the steady-state operating level.

The specified minimum net-positive-suction total pressure requirements to prevent turbopump cavitation were 4 and 8 psi (2.8 and 5.5 N/cm^2) for the hydrogen and oxygen pumps, respectively.

AC-9 Flight Results

At main-engine first cutoff, the temperature gradient from the engine combustion chamber to the aft end of the expansion nozzle can be quite large. However, the 24-minute coast period on AC-9 was considered to be of sufficient duration to permit the hotter combustion chamber to cool and the colder expansion nozzle to warm to a nearly equal temperature value representative of the average thrust-chamber metal temperature. One temperature measurement was provided near the throat of each engine thrust chamber on AC-9. At main-engine second start, these temperature measurements indicated 366° and 335° R (203 and 186 K) for the C-1 and C-2 engines, respectively. These temperature values were within the specification requirements for a satisfactory engine start.

Hydrogen and oxygen pump-housing temperatures during prestart and for the main-engine second start transient are presented in figures 26 and 27. The hydrogen pump-housing temperature decay during the prestart period was more gradual than expected. This was believed to be the result of a slow transducer response. Slow response with

particular transducers has been noted during previous flights. The oxygen pump-housing temperature response was considered satisfactory.

Hydrogen and oxygen-pump-inlet net-positive-suction pressures during prestart and for the first 5 seconds of engine operation are presented in figures 28 and 29. The engine pump-inlet temperature and total pressure values at main-engine second start are also shown in figures 24 and 25. The calculated flight values of total pressure above saturation pressure were well above the specified required values of 4 psi (2.8 N/cm^2) for the hydrogen pump and 8 psi (5.5 N/cm^2) for the oxygen pump.

Thrust-chamber pressure rise and turbopump speed rise for the main-engine second start transient are presented in figures 30 and 31. For purposes of comparison, the same parameters for the first-burn start transient are presented in figures 32 and 33. The three-standard-deviation envelopes are shown on the curves of thrust-chamber pressure rise. The rise in chamber pressure, to a level of approximately 15 psia (10.3 N/cm^2 abs), is obtained from the initial low-pressure flow. An increase in turbopump flow rate and headrise causes the abrupt rise in engine chamber pressure and pump speed at approximately 1.3 seconds following main engine start. The slight difference in slope and time of engine-chamber pressure rise between the first and second firings is considered to have resulted from the differences in thrust-chamber average metal temperature, turbopump inlet conditions, and the propellant-utilization valve setting. The differences between the first and second firing noticed on AC-9 correlated with those expected and were considered acceptable. All engine-system measurements indicated a normal thrust rise toward the steady-state operating level.

CONCLUDING REMARKS

The successful restart of the Centaur engines on AC-9 after a 24-minute Earth orbital coast verified the adequacy of the propellant management design concepts. Propellants remained settled following main-engine first cutoff, and venting of the boiloff gases during the coast was accomplished without incident. Pressurization of the propellant tanks in preparation for main-engine second start was also accomplished without any indications of major disturbances of the liquid-vapor interface.

The adequacy of the method of thermally preconditioning the propellant supply lines to the engines and preconditioning of the engine turbopumps prior to main-engine second start was satisfactorily demonstrated. Liquid conditions were established at the engine turbopump inlets within 4 seconds after the start of engine prechill. All engine performance data indicated that the restart was completely successful.

SUMMARY OF RESULTS

The AC-9 propellant management during the coast phase and thermal preconditioning of the propellant feed and engine systems for the engine restart were satisfactorily demonstrated as evidenced by the following results:

1. Only minor disturbances of the liquid hydrogen were noted at the main-engine first shutdown. These disturbances were quickly damped, and the hydrogen was settled within 10 seconds and remained settled throughout the coast phase.

2. Momentary splashing was observed in the liquid-oxygen tank at the main-engine first shutdown. These disturbances were also quickly damped and the liquid oxygen remained settled throughout the coast phase.

3. Venting of the hydrogen tank began 230 seconds after main-engine first shutdown, and continued intermittently during the coast. A total of 40 pounds (18 kg) of gaseous hydrogen was vented. Vehicle disturbances during the venting periods were negligible, indicating satisfactory operation of the balanced-thrust hydrogen vent system.

4. Pressurization of the propellant tanks for the engine restart was accomplished without any indication of propellant splashing or tank pressure collapse.

5. The liquid-hydrogen tank ullage temperature was stratified during the coast phase, engine prestart period, and the main-engine second firing period.

6. The liquid-hydrogen supply lines and the C-1 engine branch of the liquid-oxygen supply line became dry of liquid propellants during the coast phase.

7. Propellant supply-line chilldown and the return of liquid in the lines was complete after only 4 seconds of the planned 17-second inflight chilldown period.

8. All boost-pump and engine performance parameters were within expected limits, and indicated a successful restart and burn of the Centaur RL-10 engines.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 25, 1968,
491-05-00-02-22.

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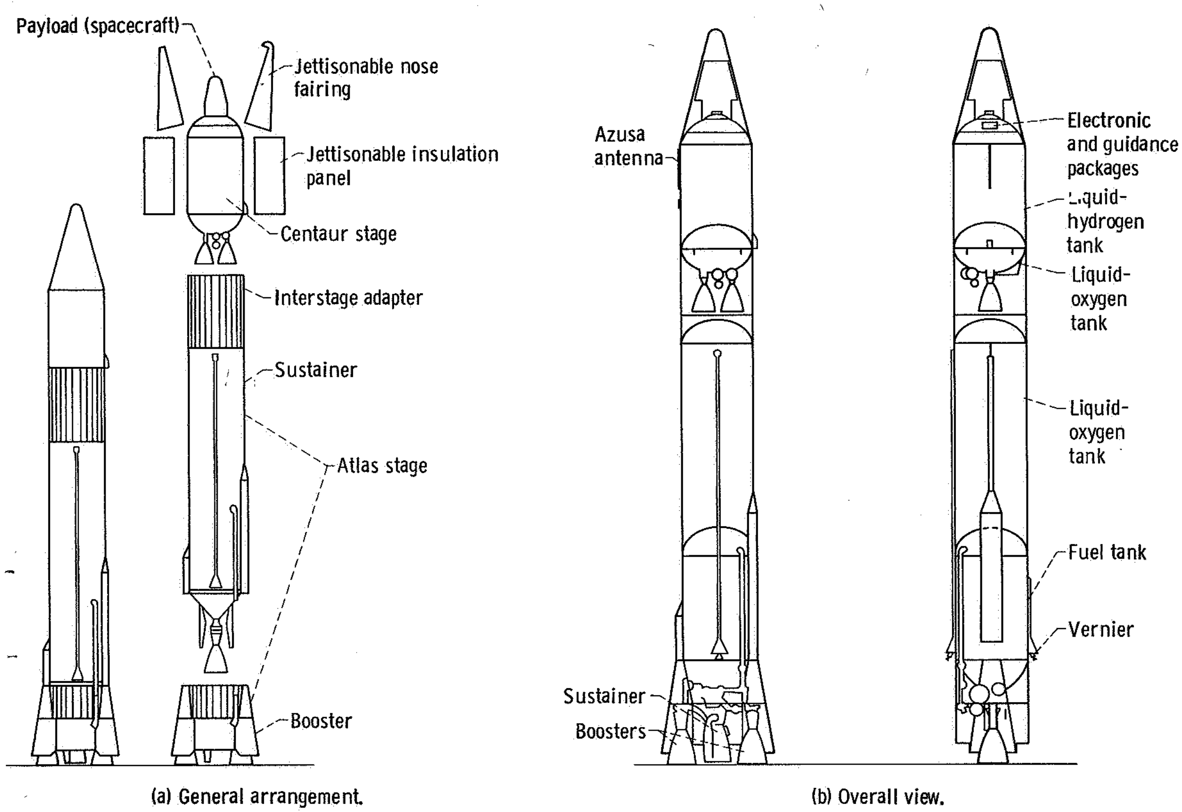
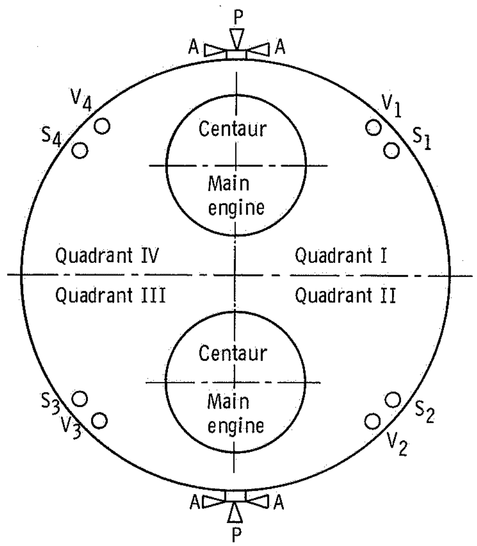


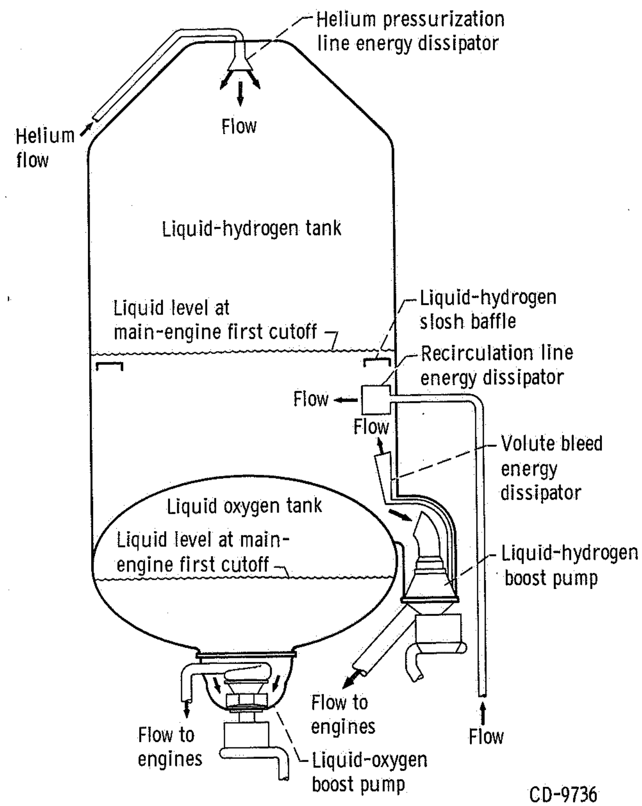
Figure 1. - Atlas-Centaur vehicle.



View looking forward

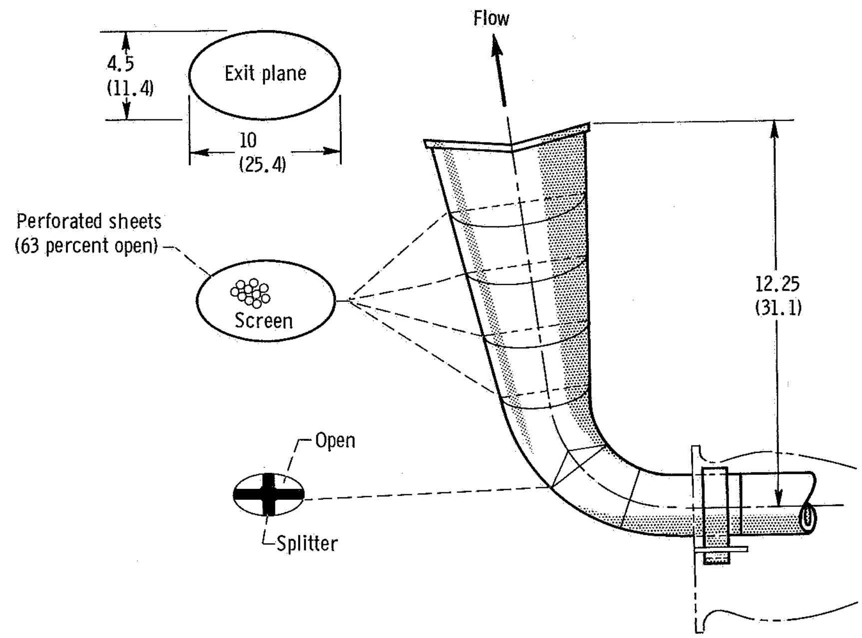
Engine designation	Thrust		Function
	lb	N	
A	3.5	15.6	Attitude control
V	50	222	Propellant settling, attitude control, and retromaneuver
P	6	26.7	Attitude control
S	3	13.3	Propellant retention and attitude control

Figure 2. - Location of AC-9 attitude control, propellant settling, and propellant retention engines.

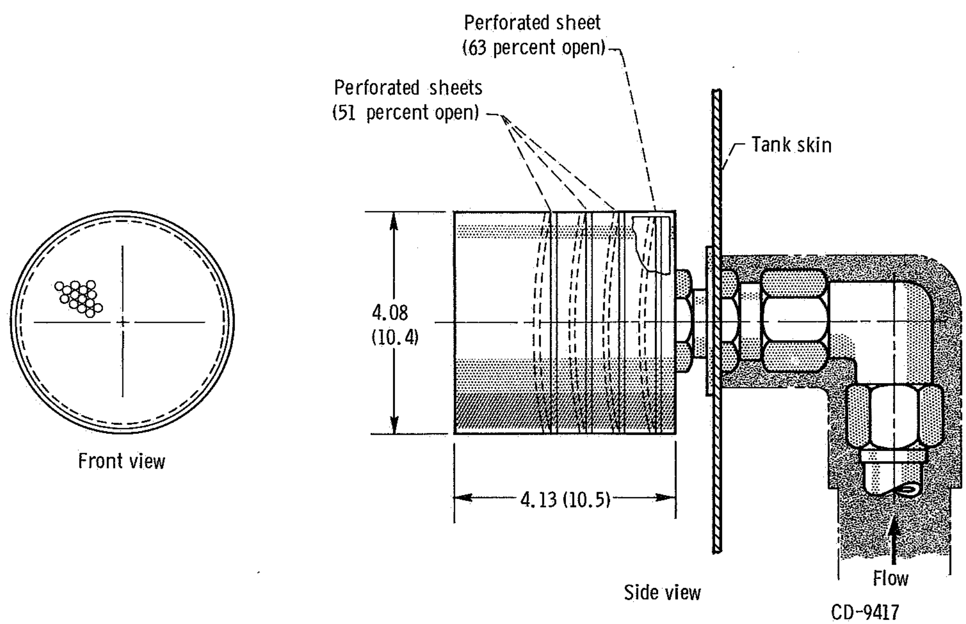


(a) Locations.

Figure 3. - AC-9 energy dissipators. (All linear dimensions are in inches (cm).)



(b) Volute bleed energy dissipator.



(c) Recirculation line energy dissipator.

Figure 3. - Concluded.

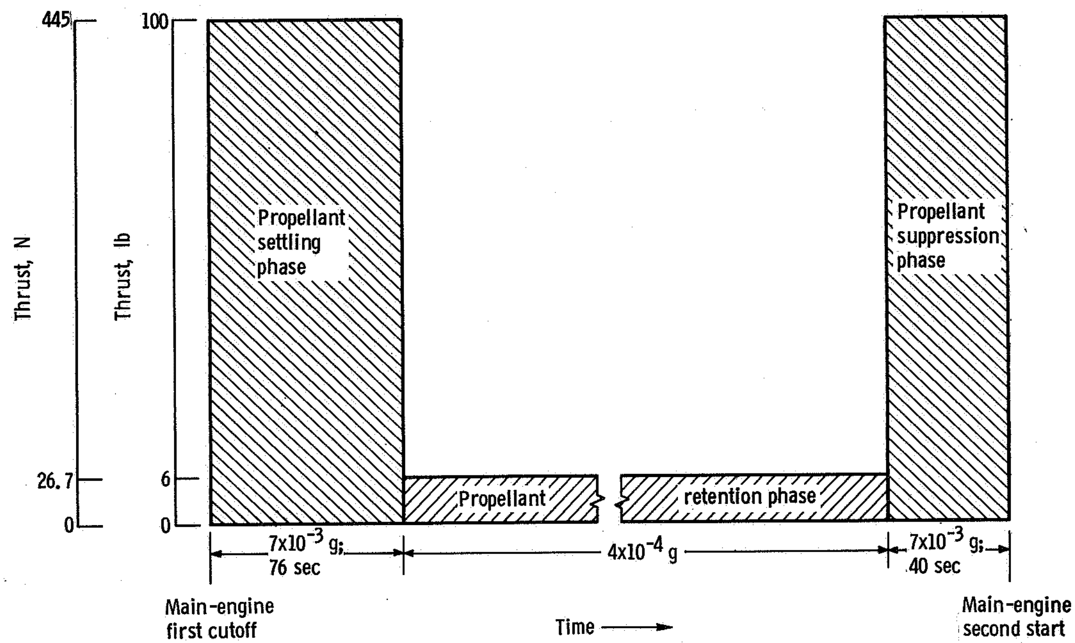


Figure 4. - AC-9 coast-phase thrust schedule.

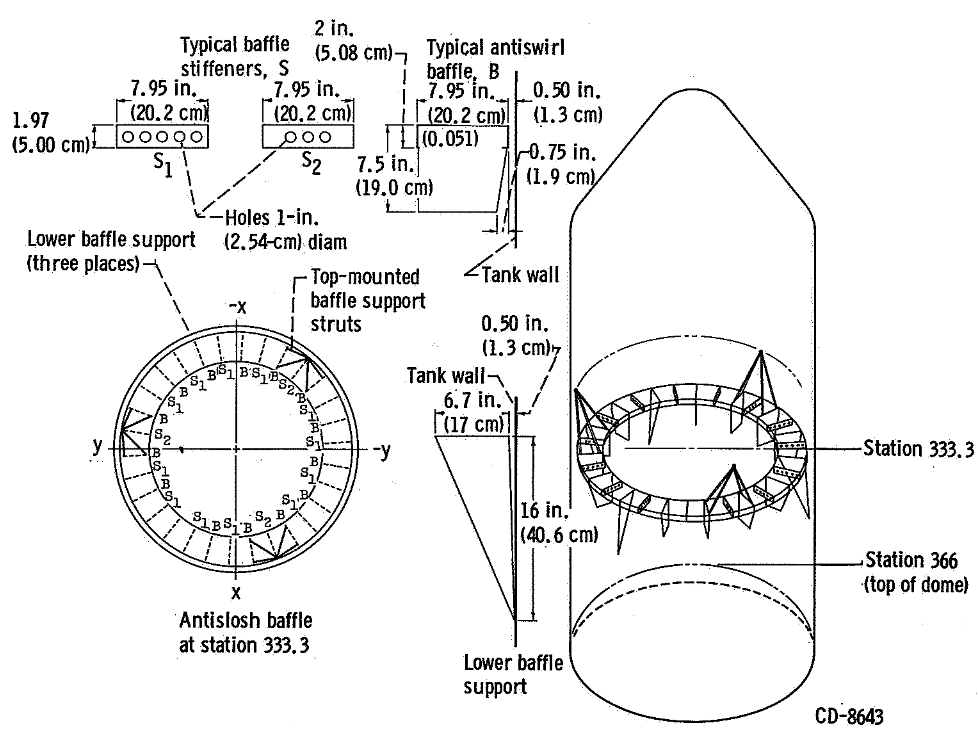


Figure 5. - AC-9 liquid-hydrogen-tank ring baffle. Station zero is top of total Atlas-Centaur vehicle. Station numbers are in inches.

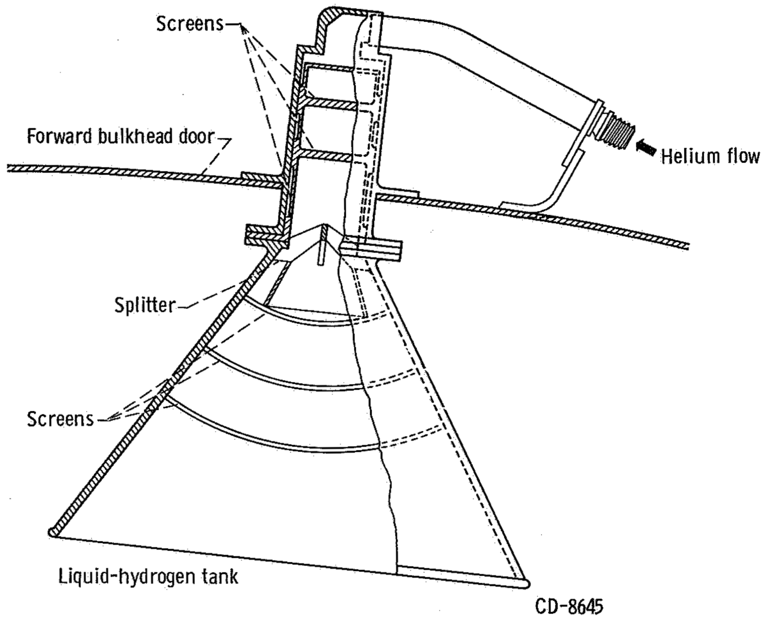


Figure 6. - Helium pressurization line energy dissipator for hydrogen tank.

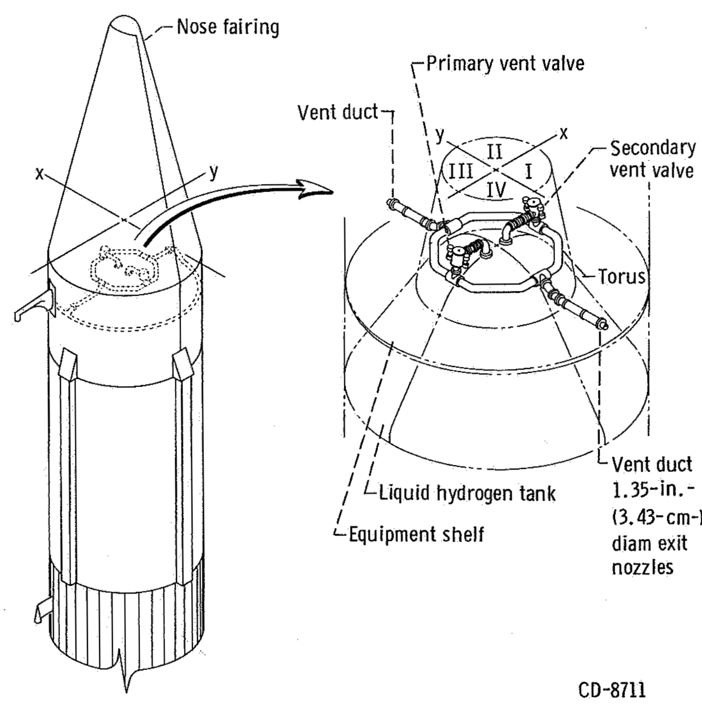


Figure 7. - Balanced-thrust hydrogen-vent system for AC-9.

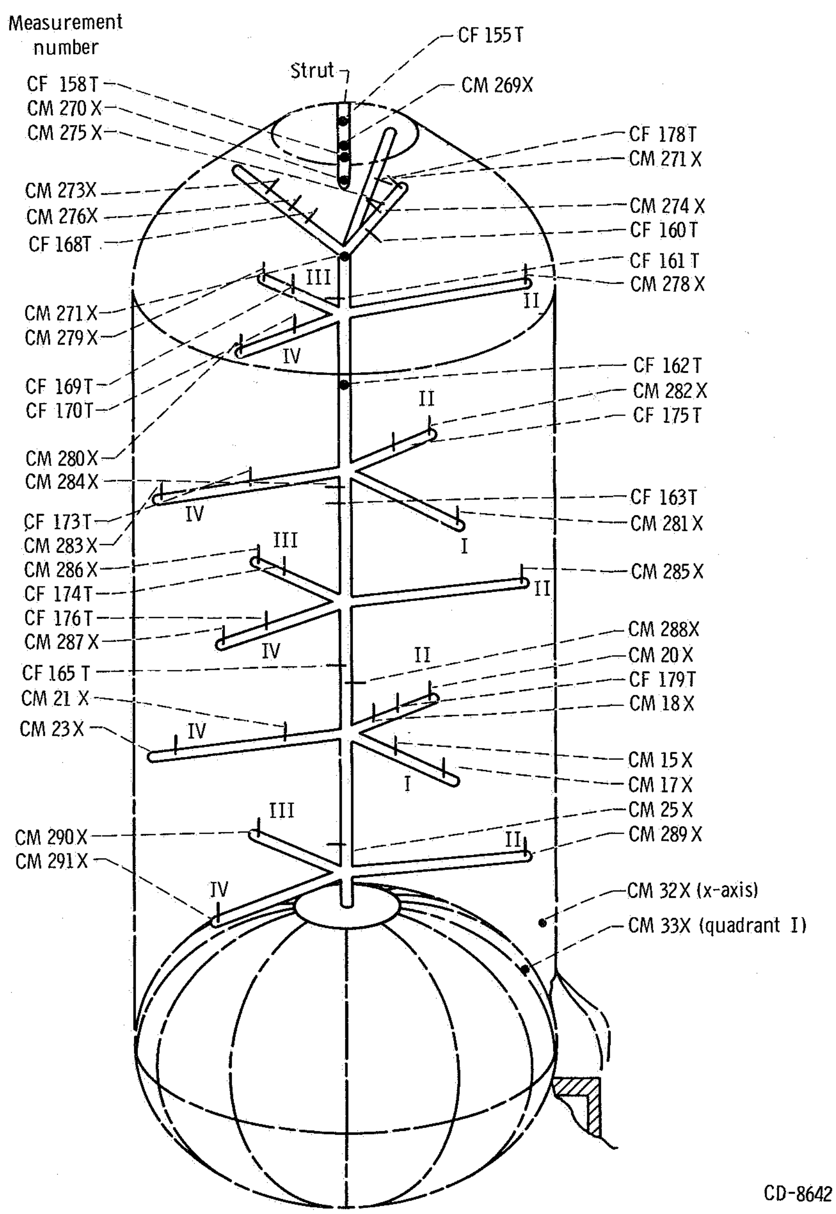


Figure 8. - AC-9 liquid-vapor sensor and ullage gas temperature sensor locations and identification. Liquid-vapor sensors denoted by X; temperature sensors denoted by T.

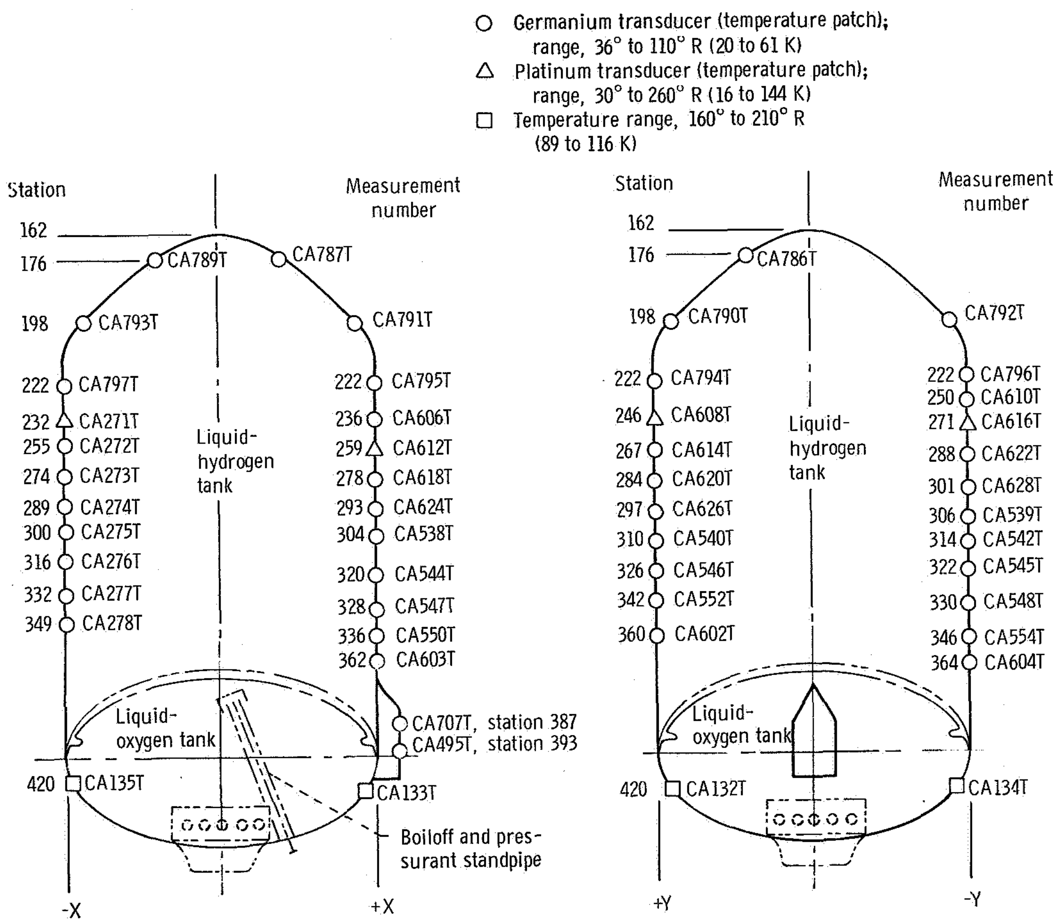


Figure 9. - AC-9 tank skin-temperature instrumentation.

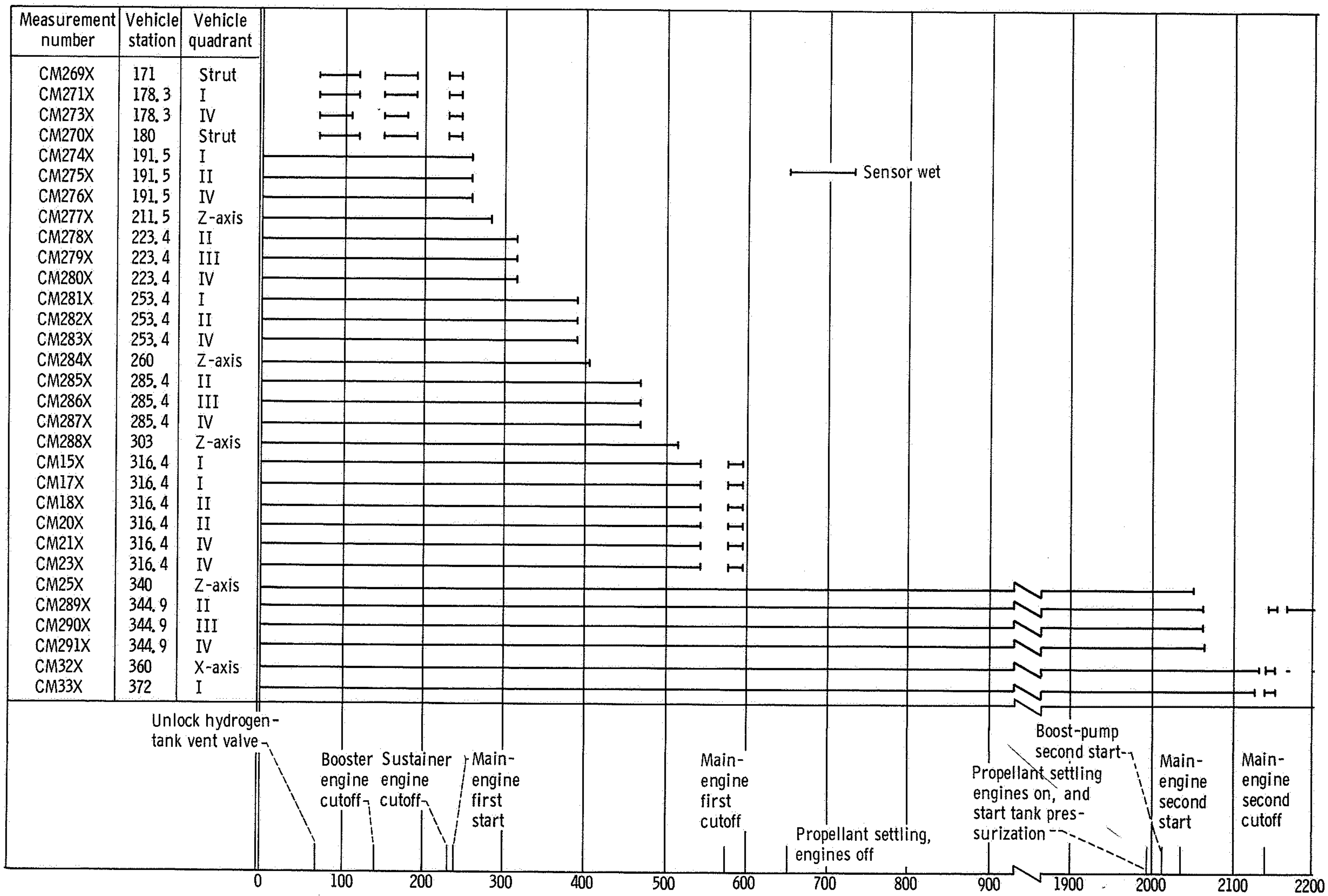
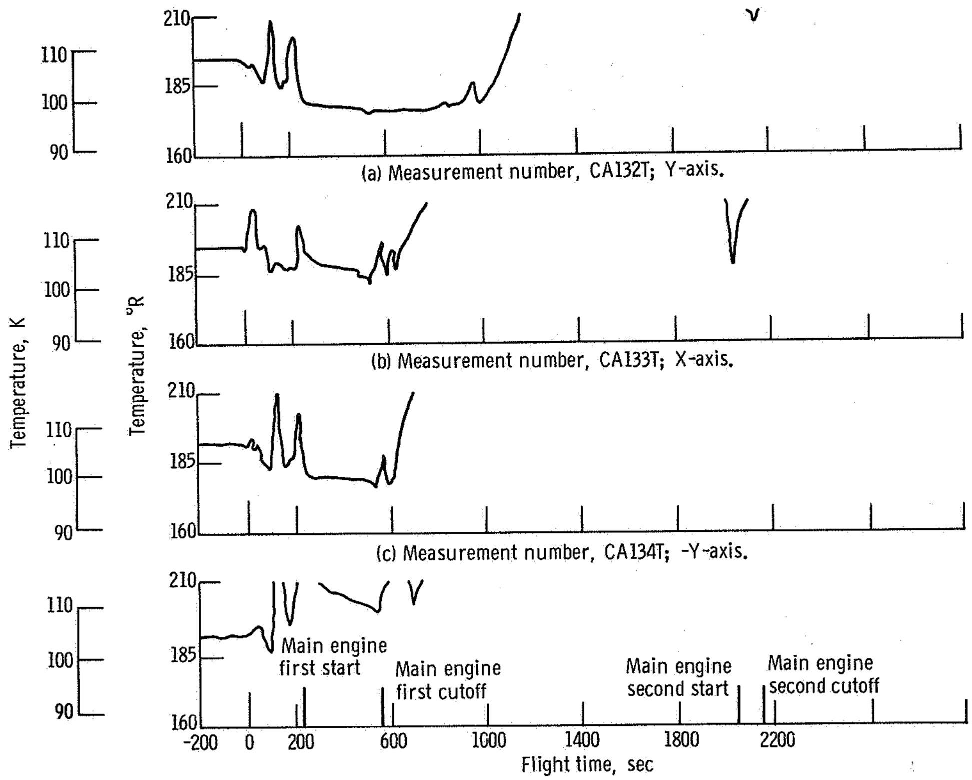
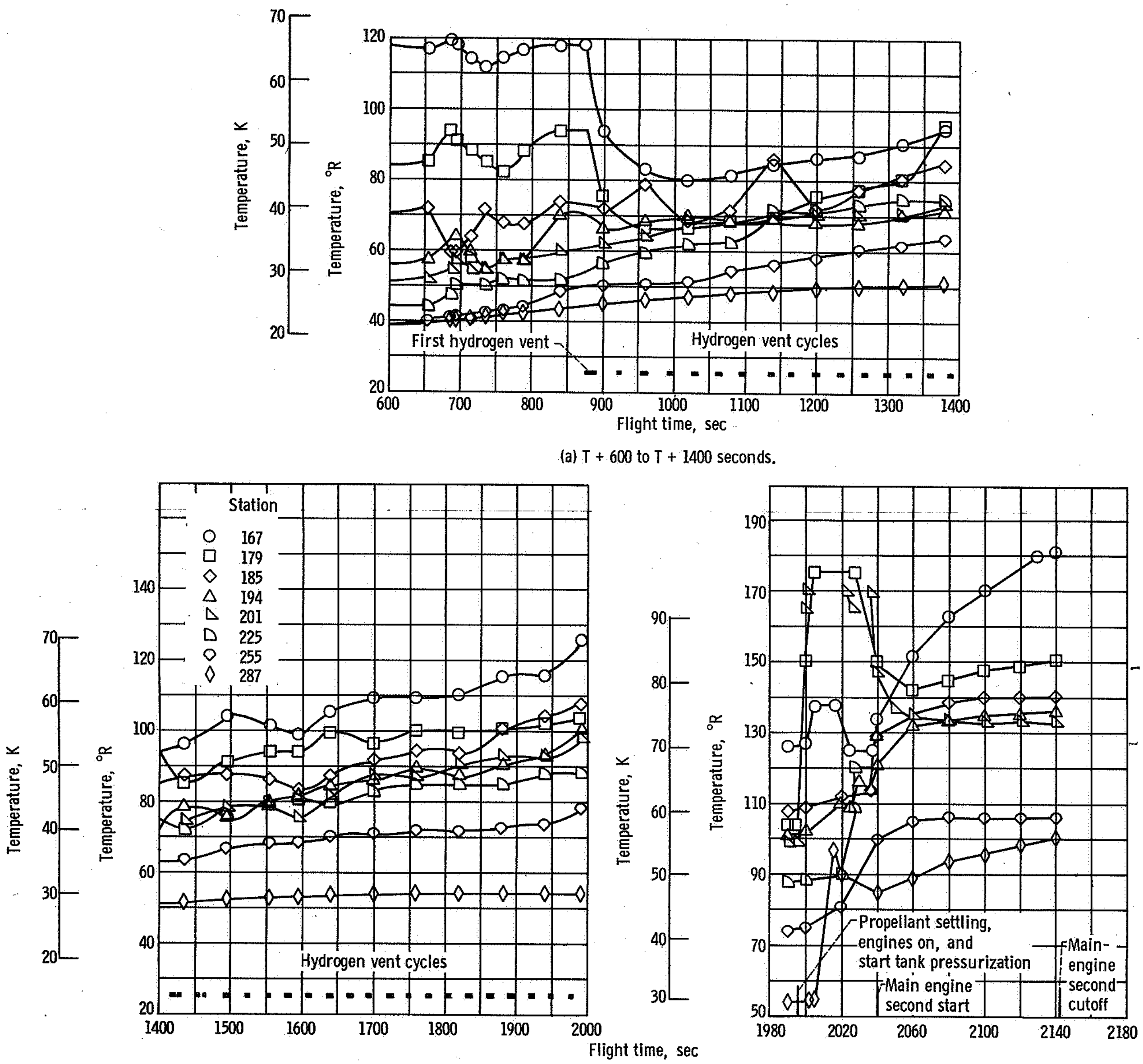


Figure 10. - AC-9 hydrogen liquid-vapor sensor indications. Measurement numbers refer to figure 8.



(d) Measurement nmuber, CA135T; -X-axis.

Figure 11. - AC-9 liquid-oxygen-tank skin temperatures; station 420.

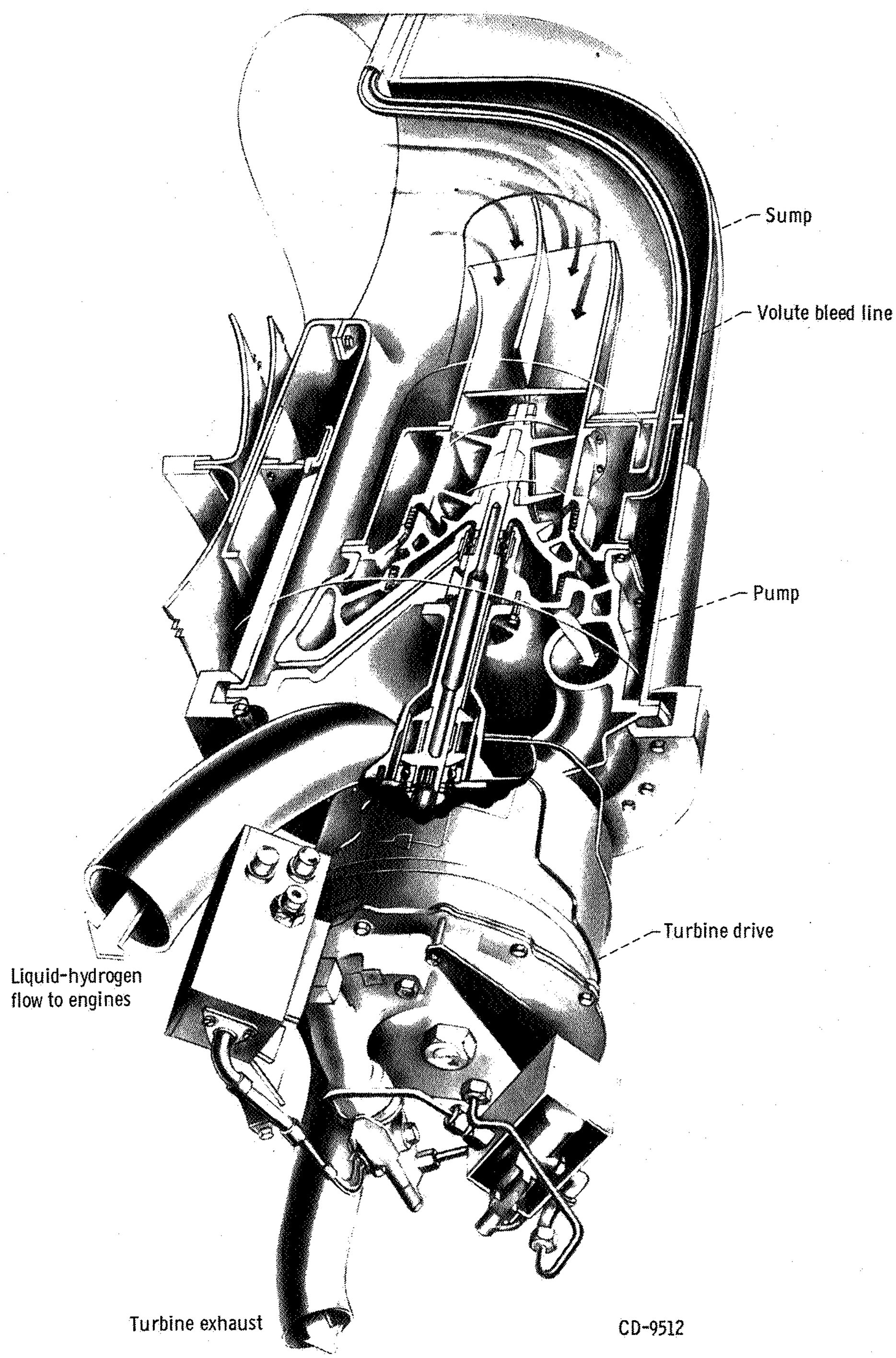


(a) T + 600 to T + 1400 seconds.

(b) T + 1400 to T + 2000 seconds.

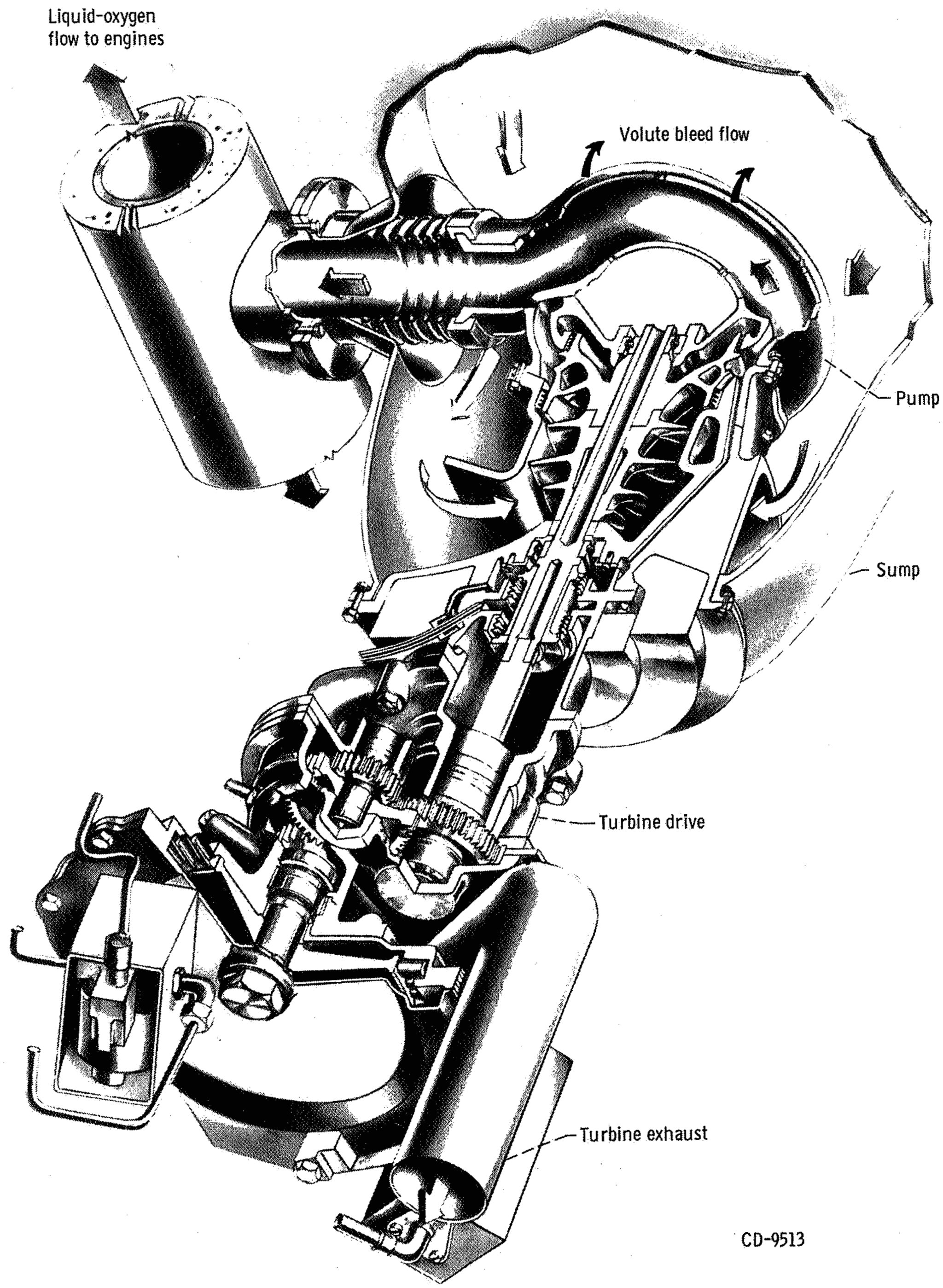
(c) T + 1980 to T + 2150 seconds.

Figure 12. - AC-9 hydrogen-tank ullage temperatures.



(a) Liquid-hydrogen boost pump.

Figure 13. - AC-9 Centaur boost-pump cutaways.



(b) Liquid-oxygen boost pump.
Figure 13. - Concluded.

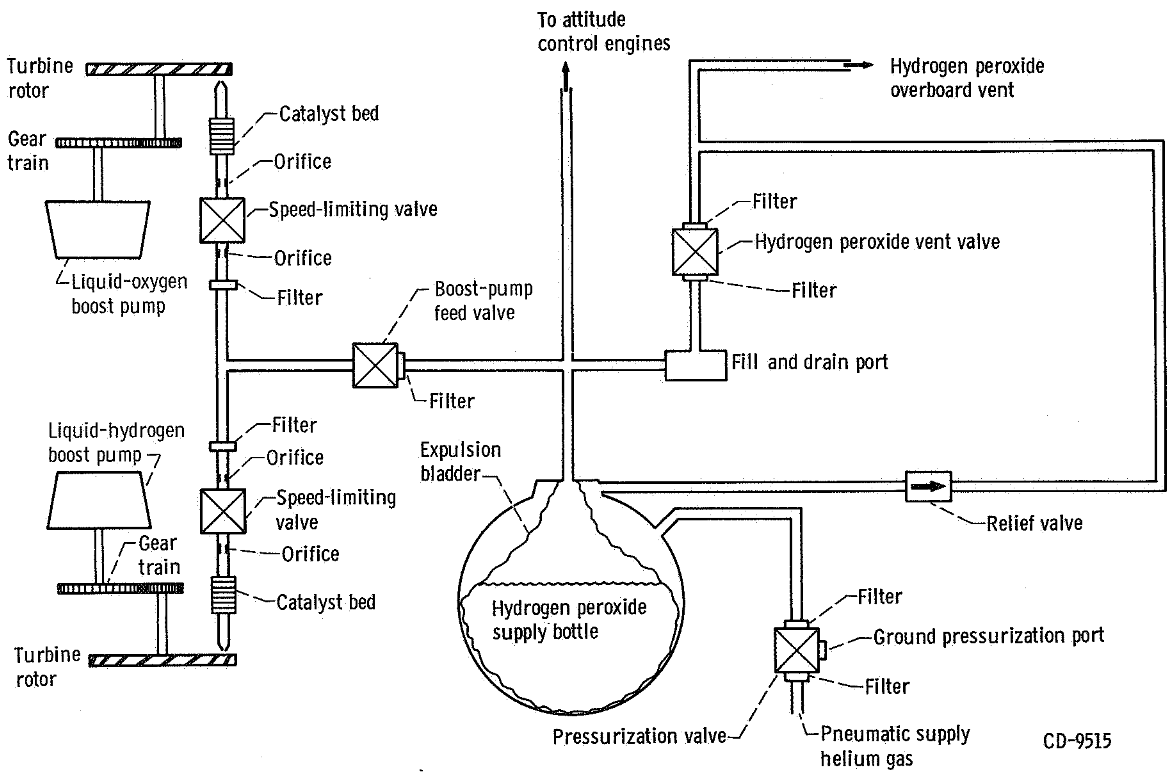


Figure 14. - AC-9 Centaur boost-pump hydrogen peroxide supply system.

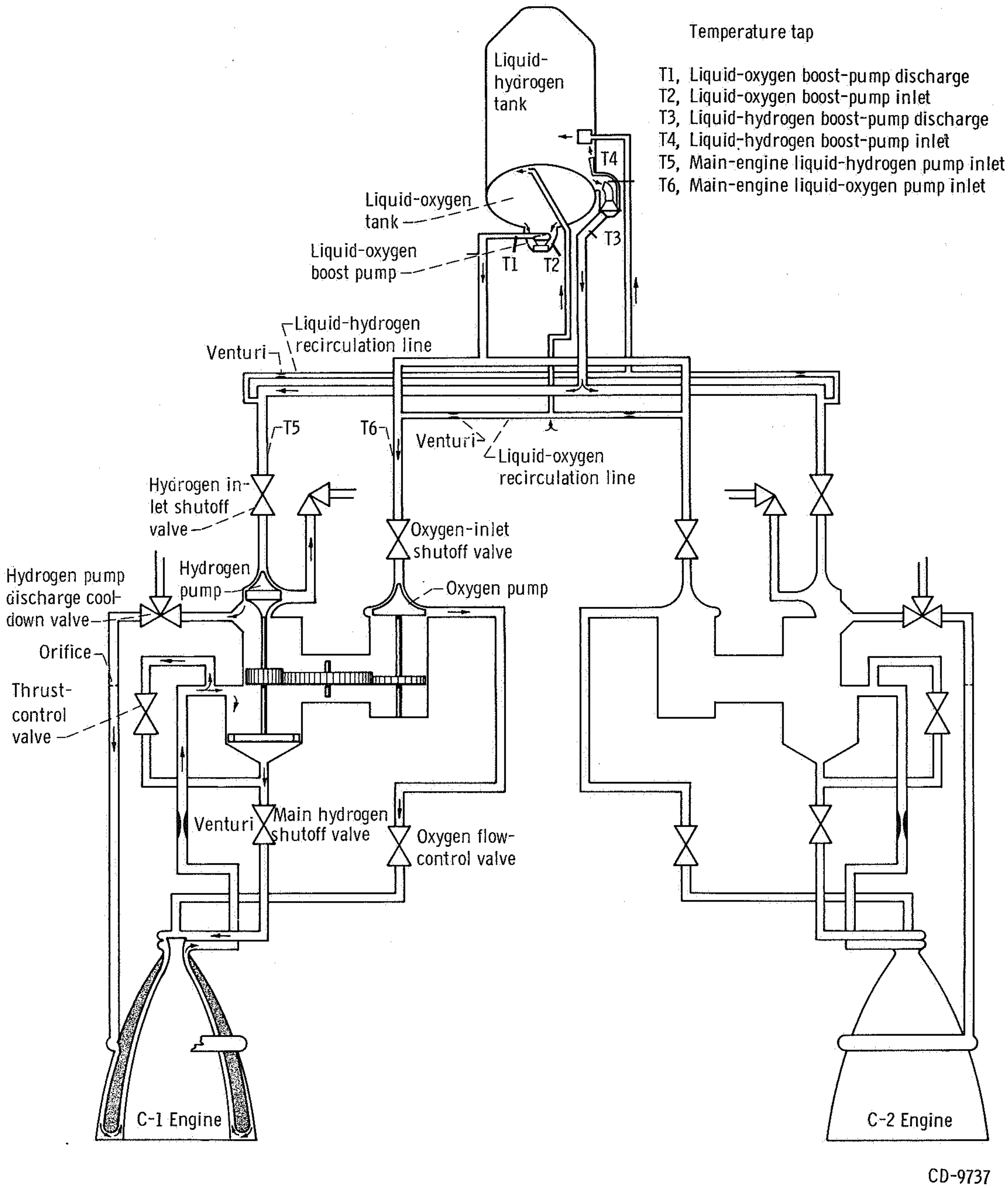


Figure 15. - Propellant supply and engine flow for AC-9.

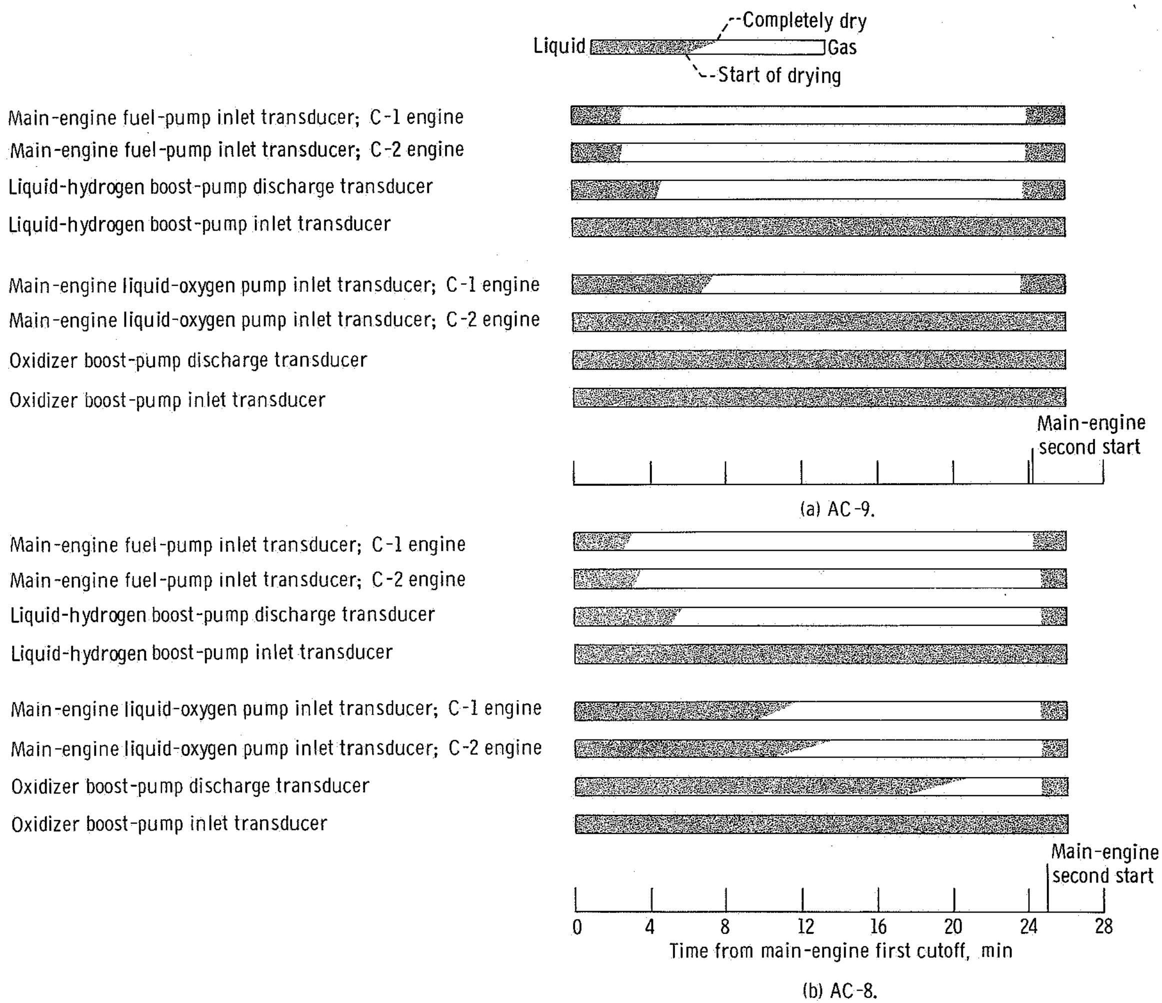


Figure 16. - Comparison of propellant supply line drying times during orbital coast on Atlas-Centaur flights AC-8 and AC-9.

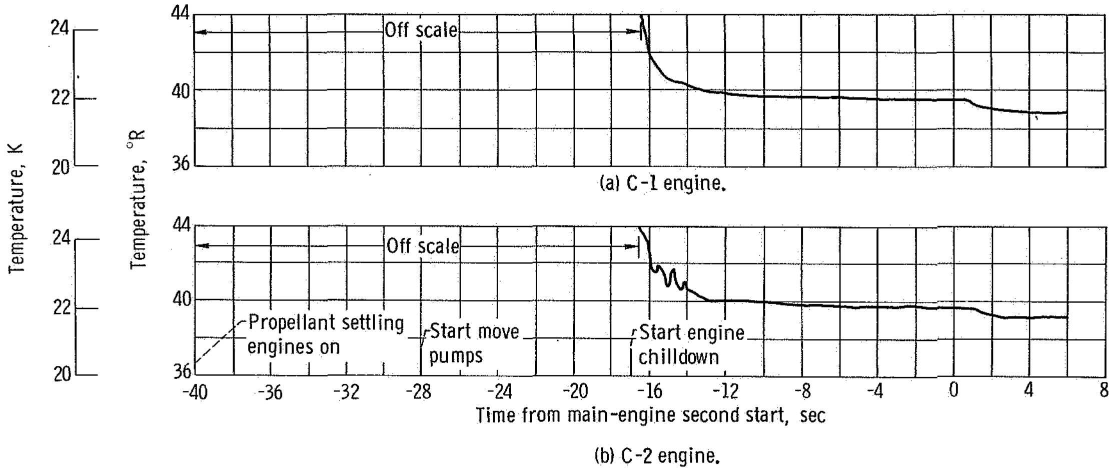


Figure 17. - AC-9 Centaur engine liquid-hydrogen pump-inlet temperature during second start sequence. Time of main-engine second start, T + 2035 seconds.

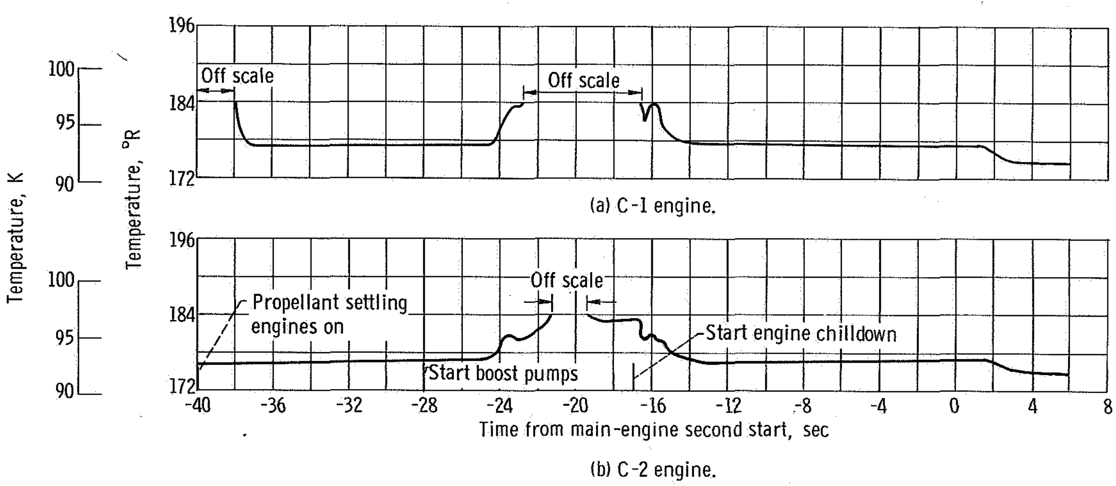


Figure 18. - AC-9 Centaur engine liquid-oxygen pump inlet temperature during second start sequence. Time of main-engine second start, T + 2035 seconds.

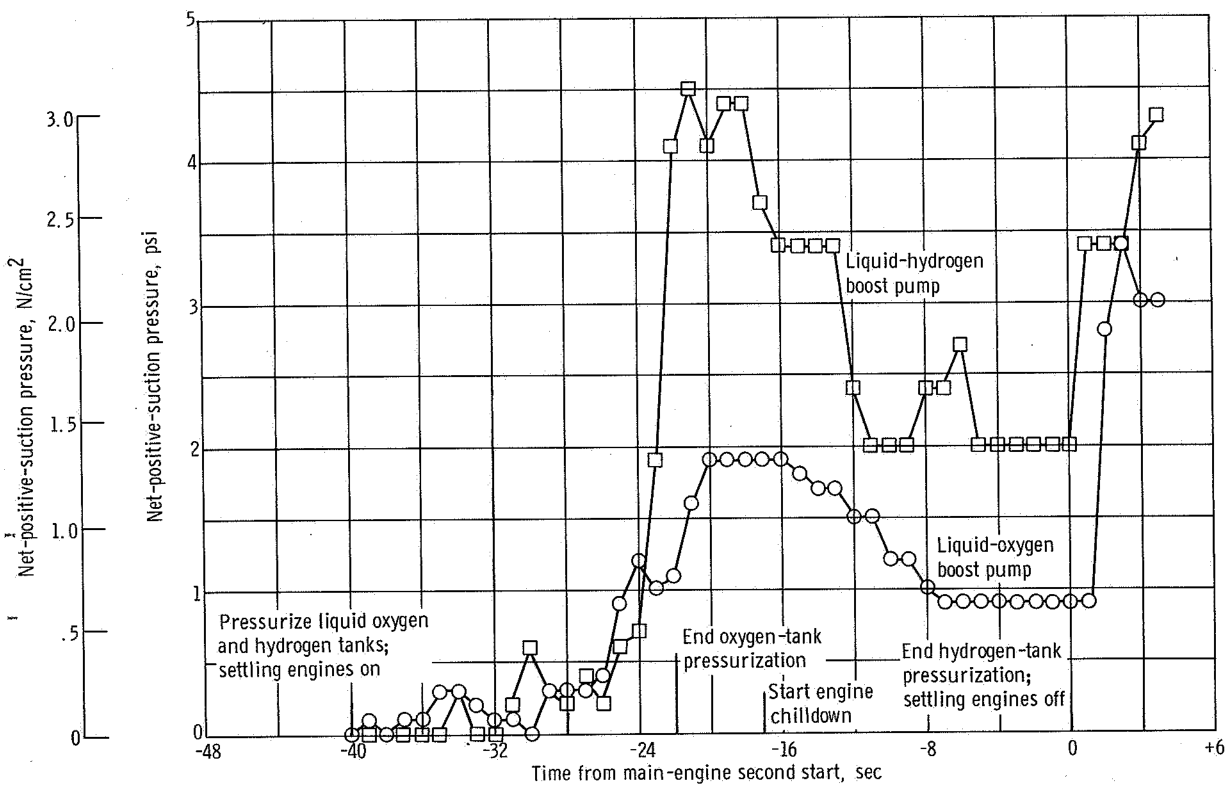


Figure 19. - AC-9 Centaur boost-pump inlet net positive suction pressure history during engine second start sequence. Time of main-engine second start, T + 2035 seconds.

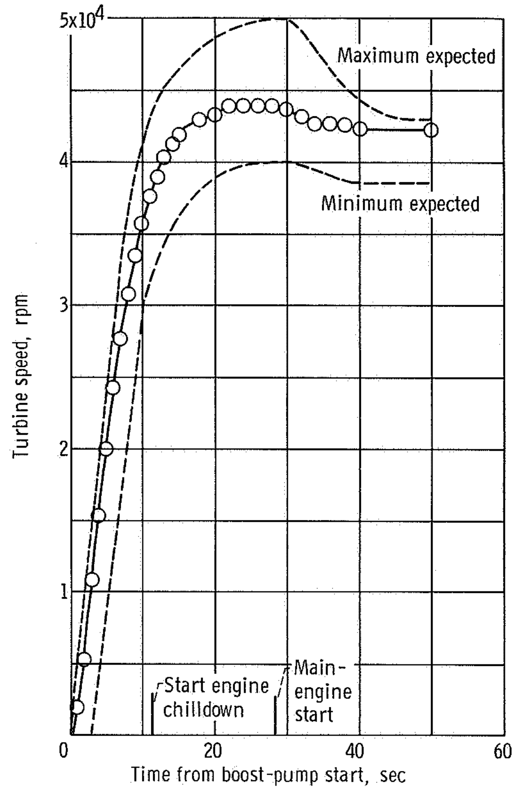


Figure 20. - AC-9 Centaur liquid-hydrogen boost-pump turbine speed; second start sequence. Time of boost-pump second start, T + 2007 seconds.

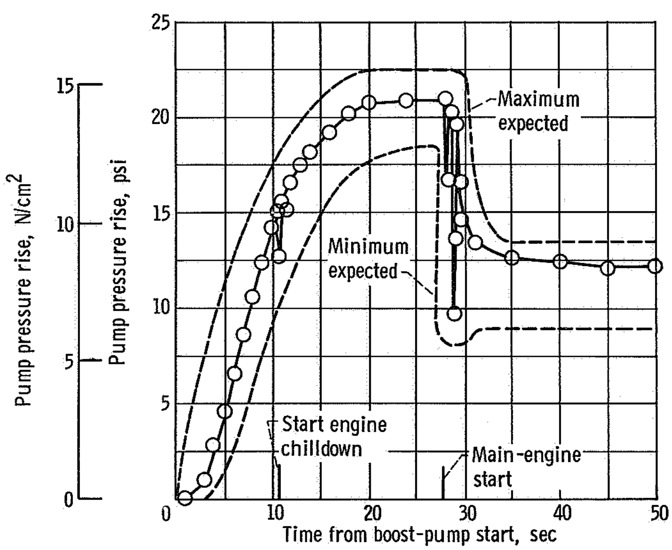


Figure 21. - AC-9 Centaur liquid-hydrogen boost-pump pressure rise; second start sequence. Time of boost-pump second start, T + 2007 seconds.

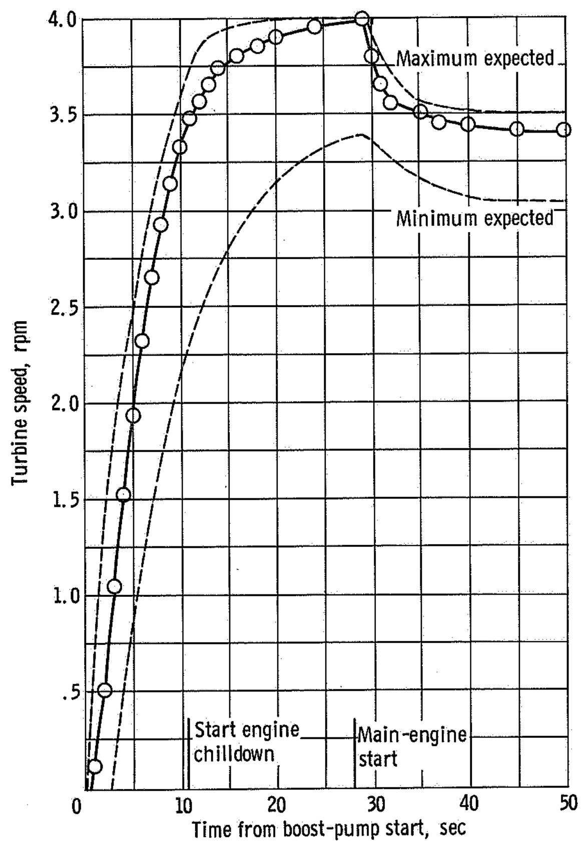


Figure 22. - AC-9 Centaur liquid-oxygen boost-pump turbine speed; second start sequence. Time of boost-pump second start, T + 2007 seconds.

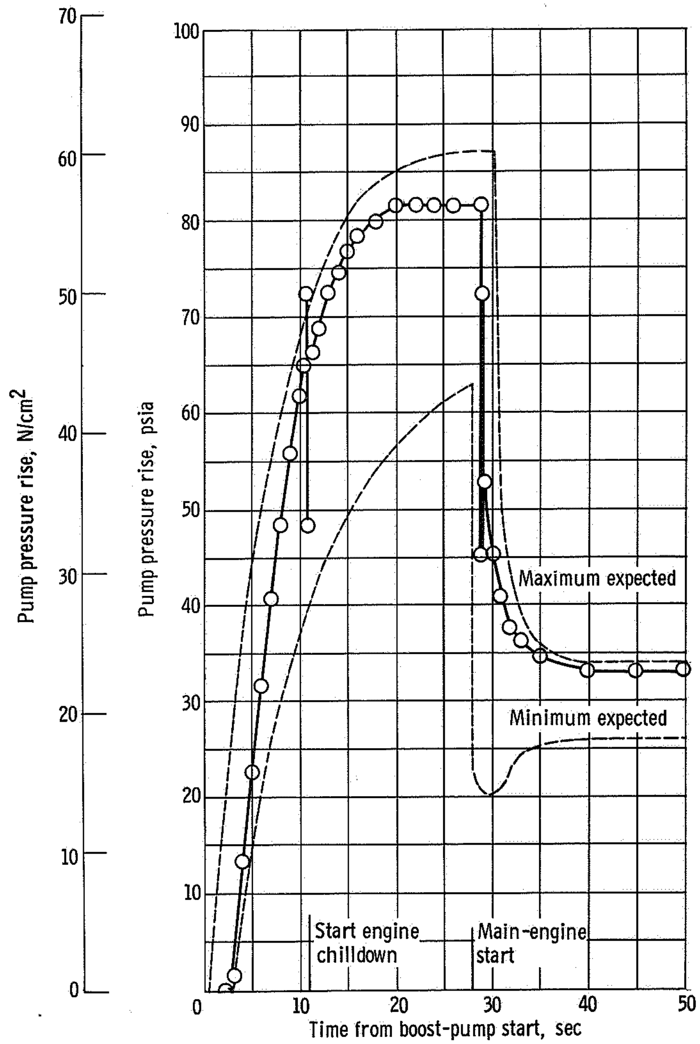


Figure 23. - AC-9 Centaur liquid-oxygen boost-pump pressure rise; second start sequence. Time of boost-pump second start, T + 2007 seconds.

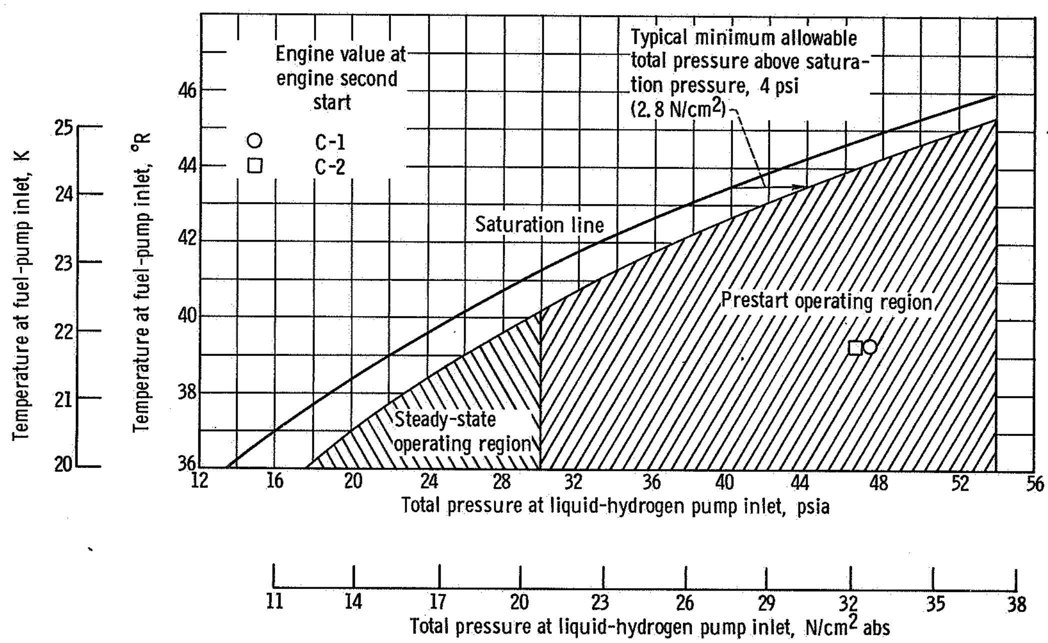


Figure 24. - Required liquid-hydrogen pressure and temperature at main-engine pump inlet.

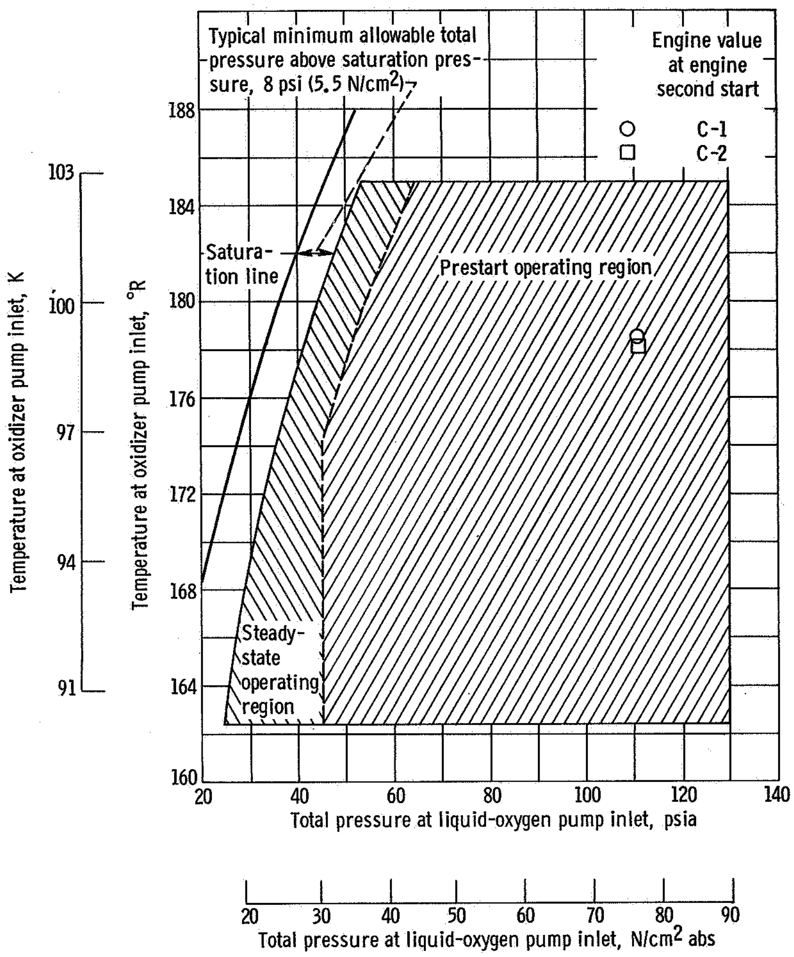


Figure 25. - Required liquid-oxygen pressure and temperature at main-engine pump inlet.

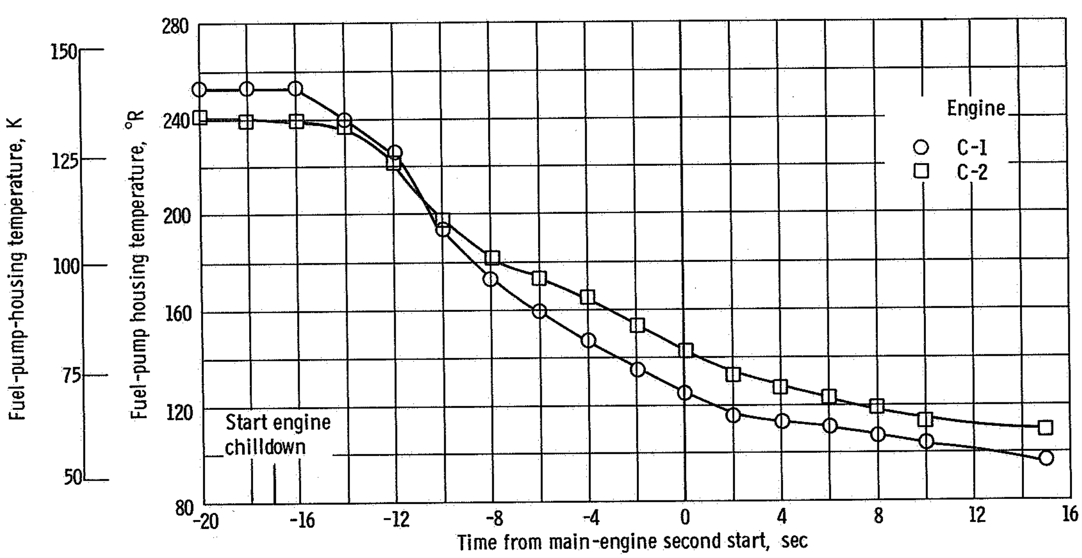


Figure 26. - AC-9 Centaur engine liquid-hydrogen pump housing temperature at main-engine second start. Time of main-engine second start, T + 2035 seconds.

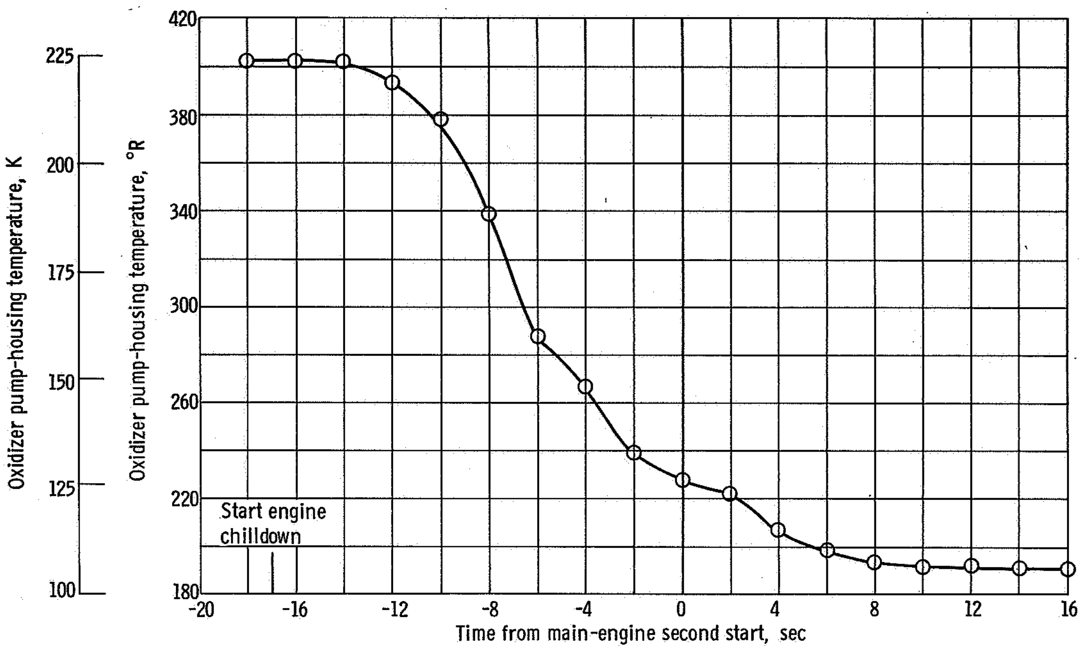


Figure 27. - AC-9 Centaur engine liquid-oxygen pump housing temperature at main-engine second start for C-1 engine. (C-2 engine data were invalid.) Time of main-engine second start, T + 2035 seconds.

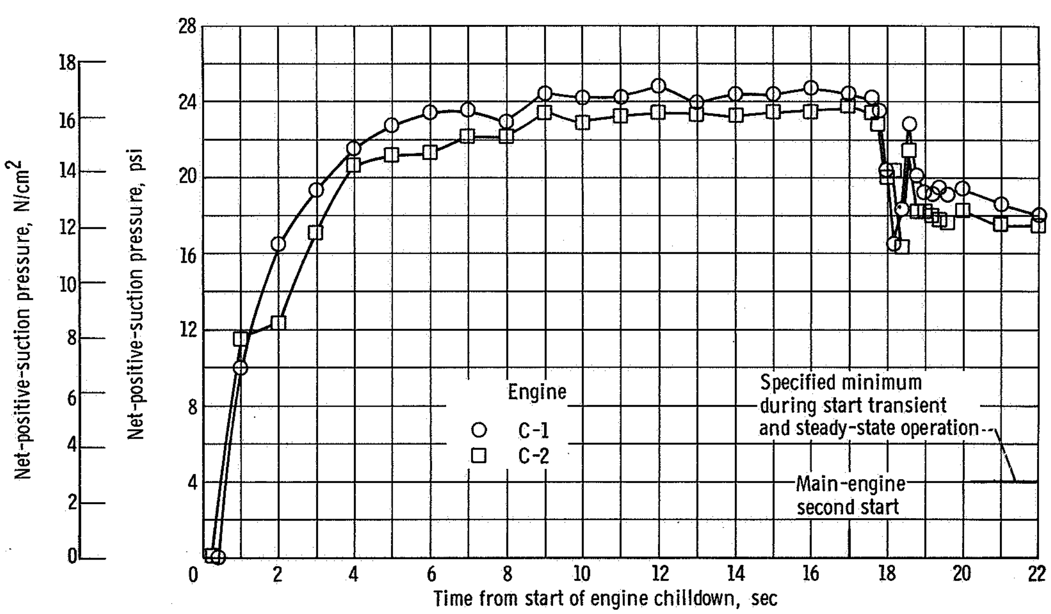


Figure 28. - AC-9 Centaur main-engine hydrogen-pump inlet net-positive-suction pressure during second start sequence. Time of start of engine chilldown (prestart), T + 2018 seconds.

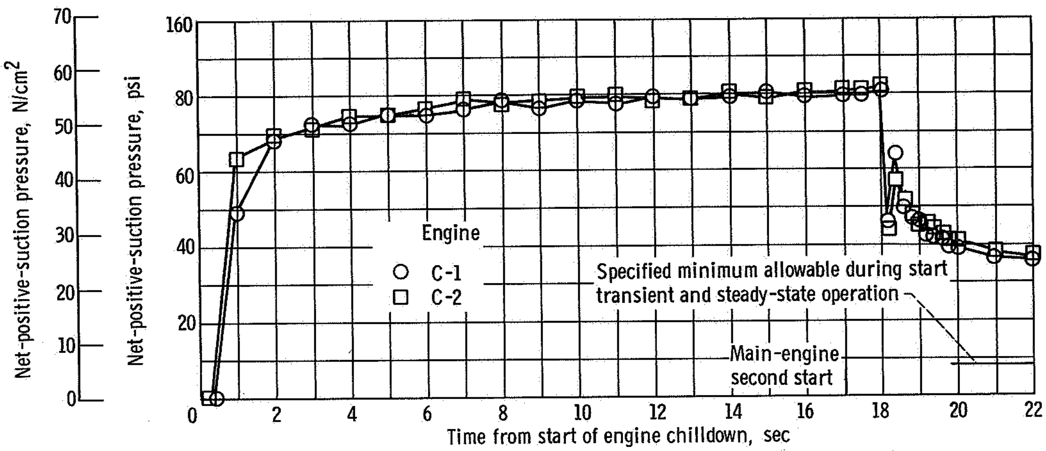


Figure 29. - AC-9 Centaur main-engine oxygen-pump inlet net-positive-suction pressure during second start sequence. Time of start of engine chilldown (prestart), T + 2018 seconds.

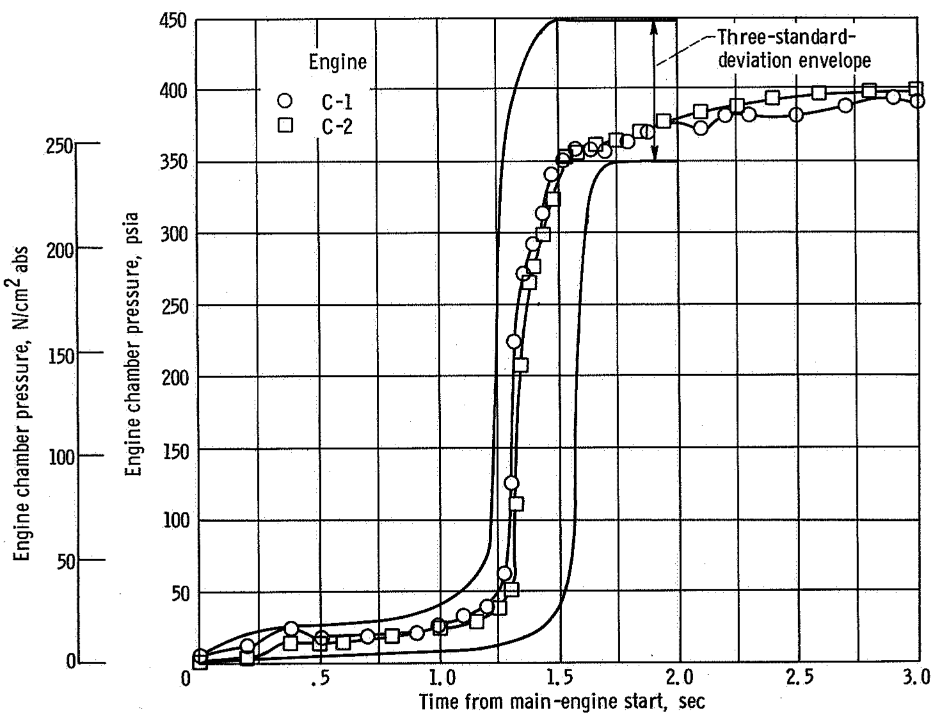


Figure 30. - AC-9 Centaur engine chamber pressure during second start transient. Time of main-engine second start, T + 2035 seconds. Three-standard-deviation envelope with (1) oxygen temperature and pressure at start, 178.2° R (99.0 K) and 115.0 psia (79.3 N/cm²), respectively, and hydrogen temperature and pressure at start, 39.3° R (21.8 K) and 40.1 psia (27.6 N/cm²), respectively; and (2) nominal thrust-chamber metal temperature at prestart, 540° R (300 K).

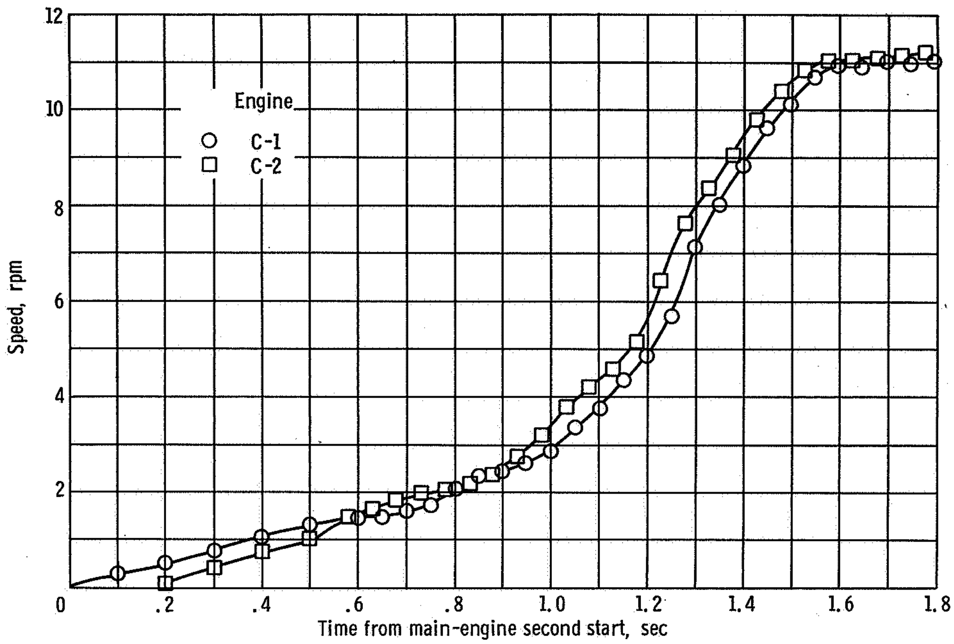


Figure 31. - AC-9 Centaur engine liquid-oxygen pump speed rise during second start transient. Time of main-engine second start, T + 2035 seconds.

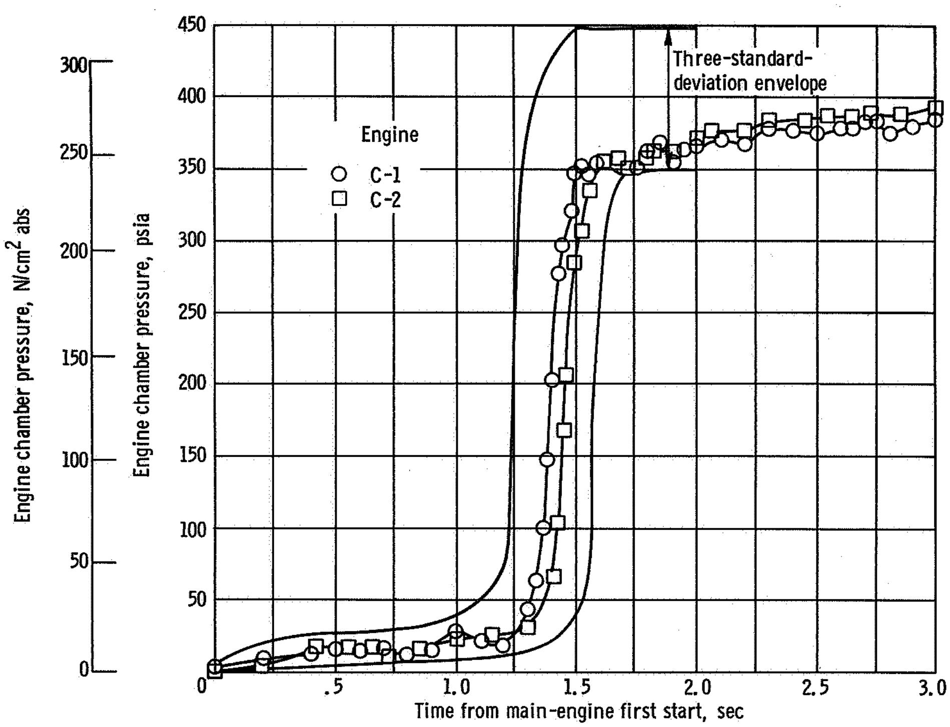


Figure 32. - AC-9 Centaur engine chamber pressure during first start transient. Time of main-engine first start, T + 240 seconds. Three-standard-deviation envelope with (1) oxygen temperature and pressure at start, 178.2° R (99.0 K) and 115.0 psia (79.3 N/cm^2), respectively, and hydrogen temperature and pressure at start, 39.3° R (21.8 K) and 40.1 psia (27.6 N/cm^2), respectively; and (2) nominal thrust-chamber metal temperature at prestart, 540° R (300 K).

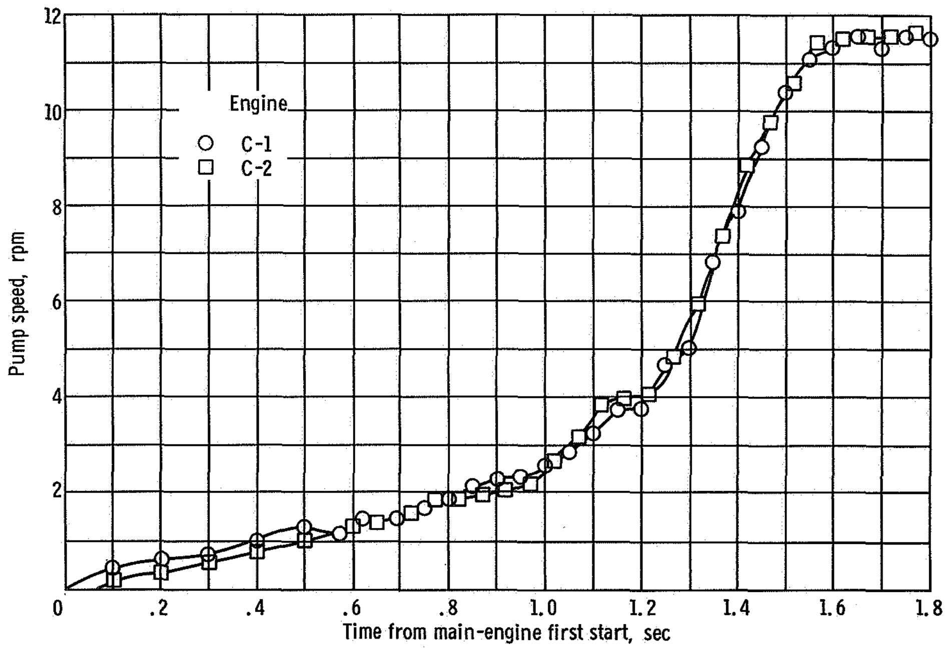


Figure 33. - AC-9 Centaur engine liquid-oxygen pump speed rise during first start transient. Time of main-engine first start, T + 240 seconds.

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